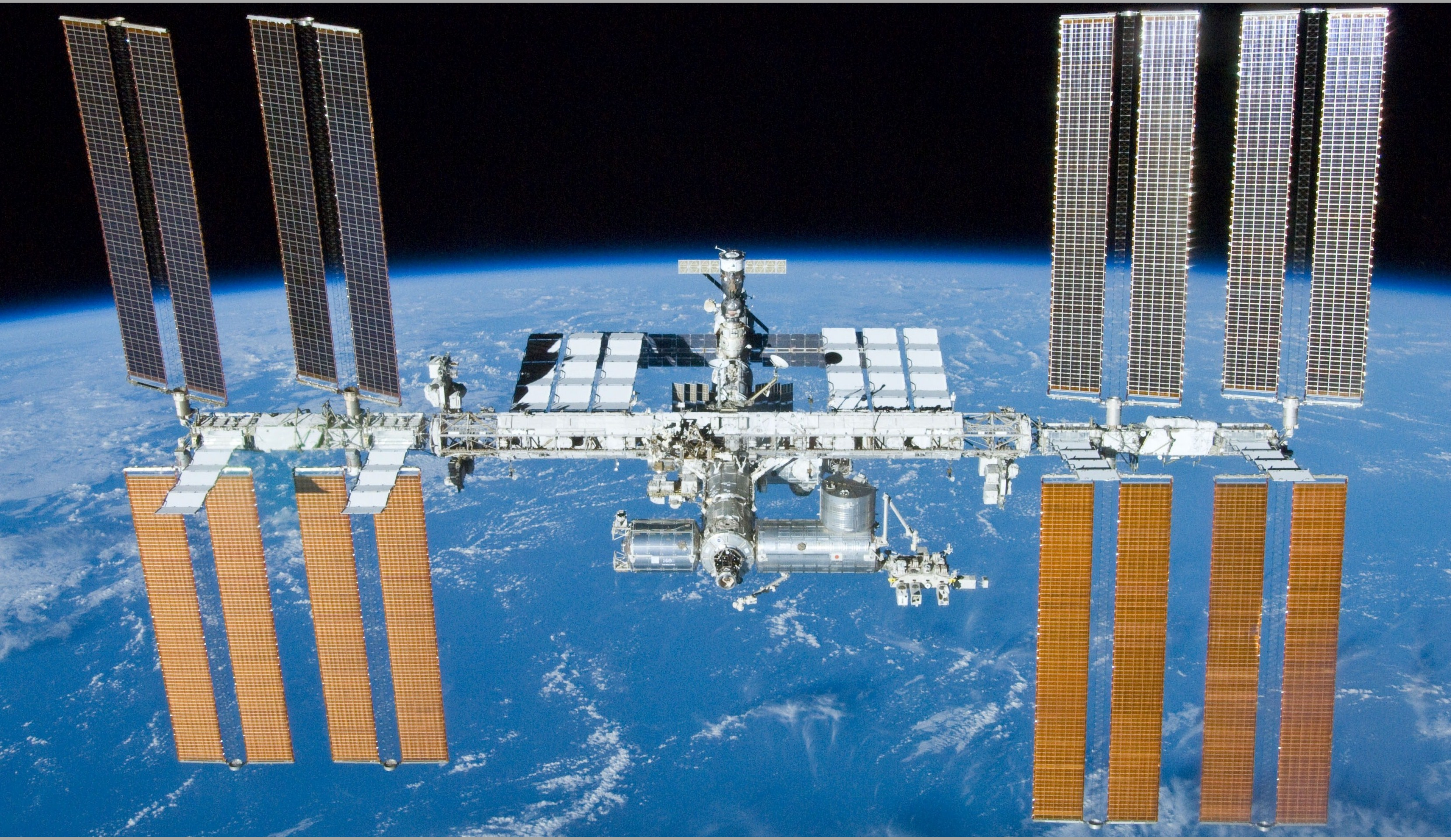
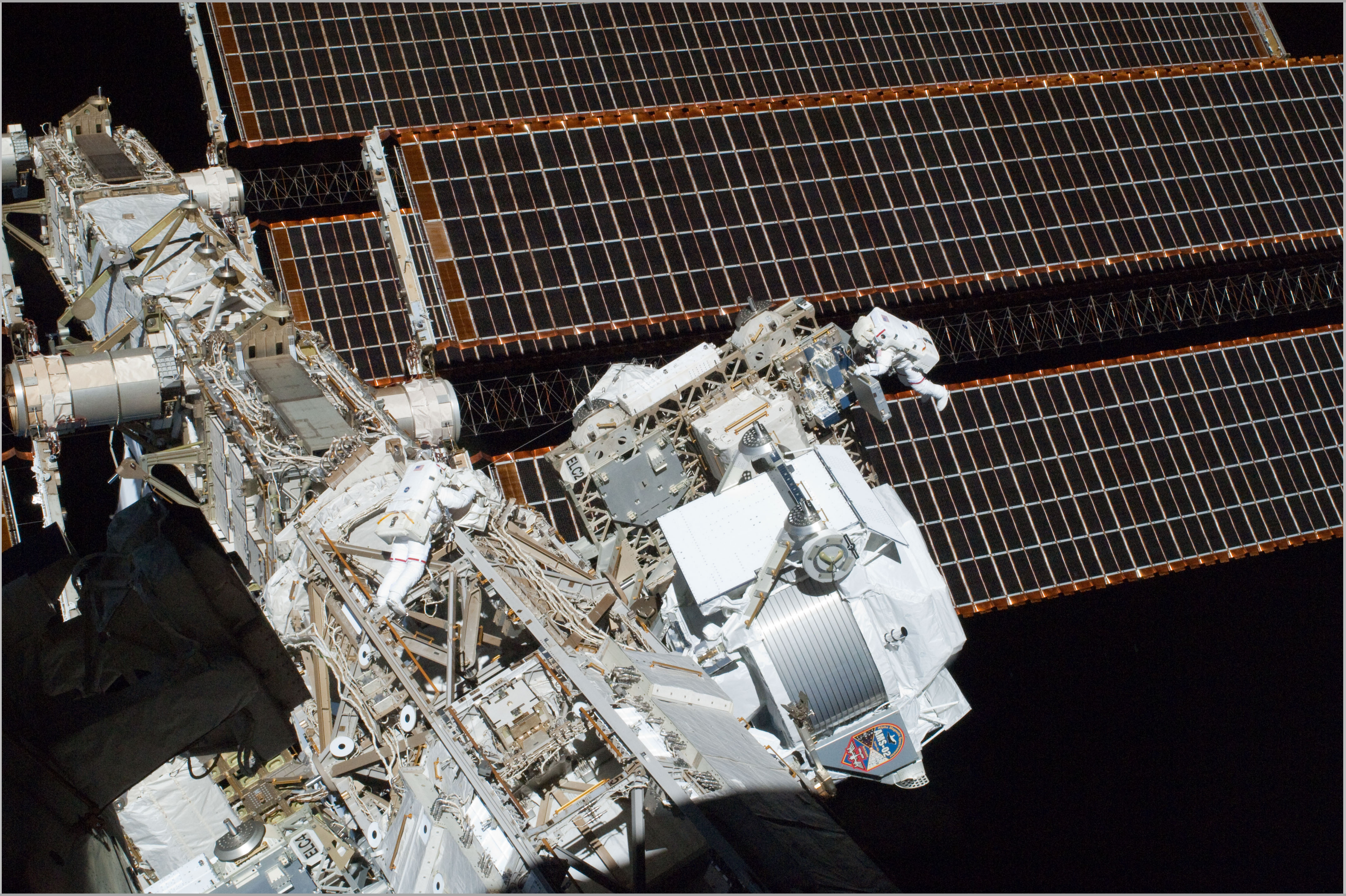

NICER
Neutron star Interior Composition ExploreR
A NICER View — Astrophysics and Exploration from the International Space Station
Zaven Arzoumanian
NASA
GSFC
MIT KAVLI INSTITUTE
DTU
BROAD REACH
MOOG

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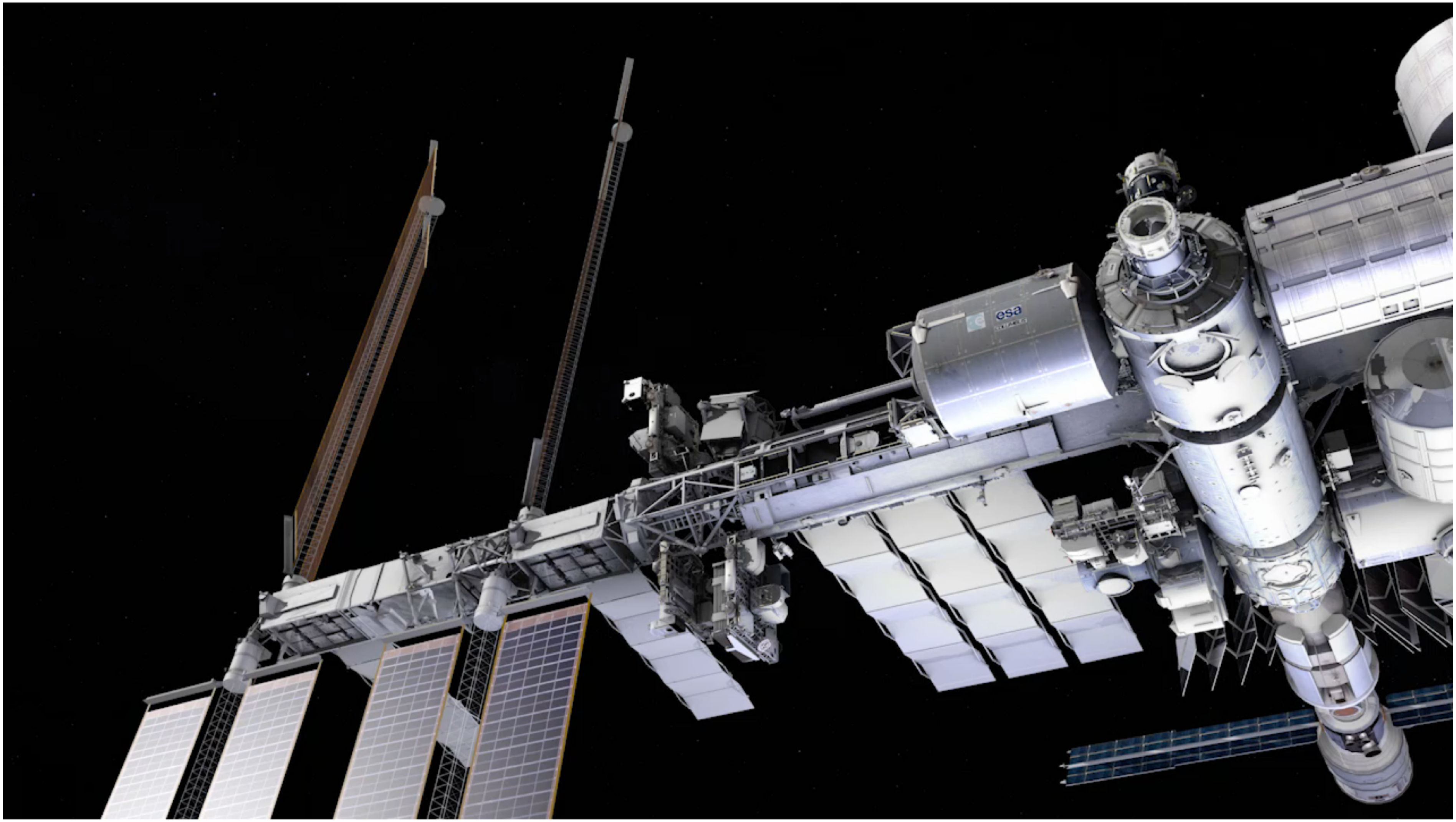
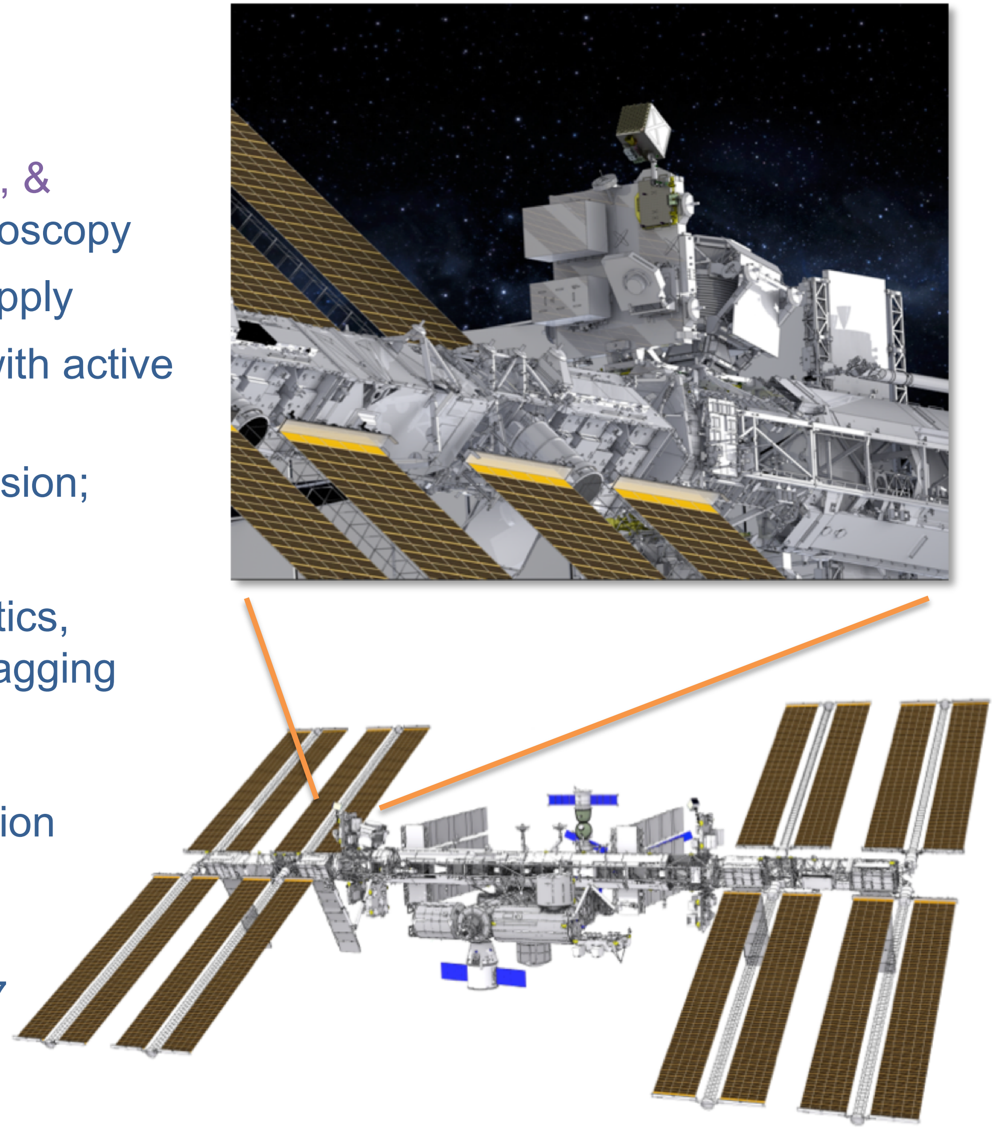
# NICER at home on ISS



# NICER/SEXTANT — Overview

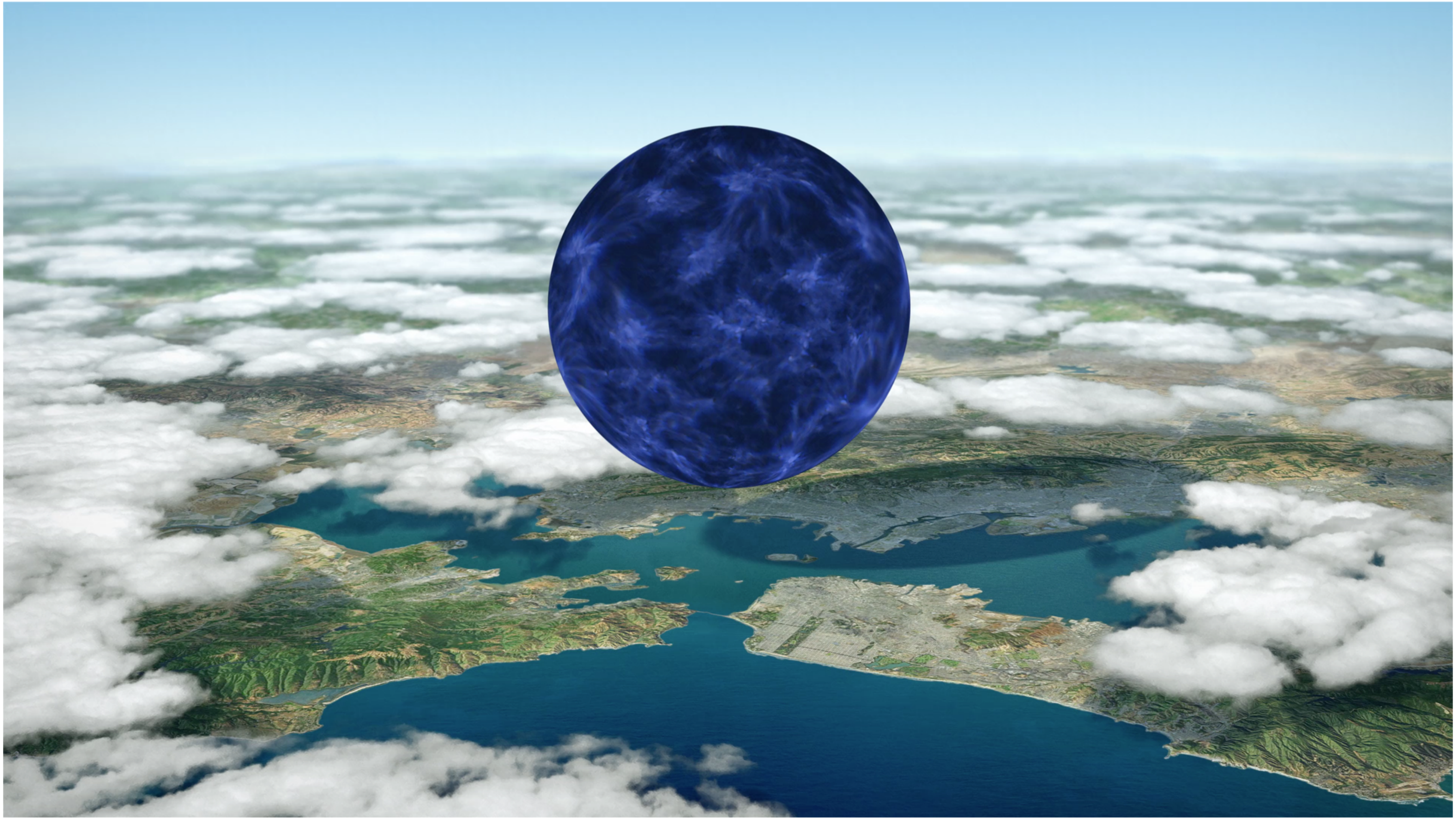
- ***PI:*** Keith Gendreau, NASA GSFC
- ***Science:*** Neutron star structure, dynamics, & energetics through soft X-ray timing spectroscopy
- ***Launched***: June 3, 2017, SpaceX-11 resupply
- ***Platform:*** ISS external attached payload with active pointing
- ***Duration:*** 18 months baseline science mission; likely GO extension
- ***Instrument:*** 0.2–12 keV "concentrator" optics, silicon-drift detectors, GPS absolute time tagging and position
- ***Enhancements:***
  - Demonstration of pulsar-based navigation
  - PI discretionary & ToO time
- ***Status:***
  - Commissioning complete 17 July, 2017
  - Baseline science mission in progress



# Outline

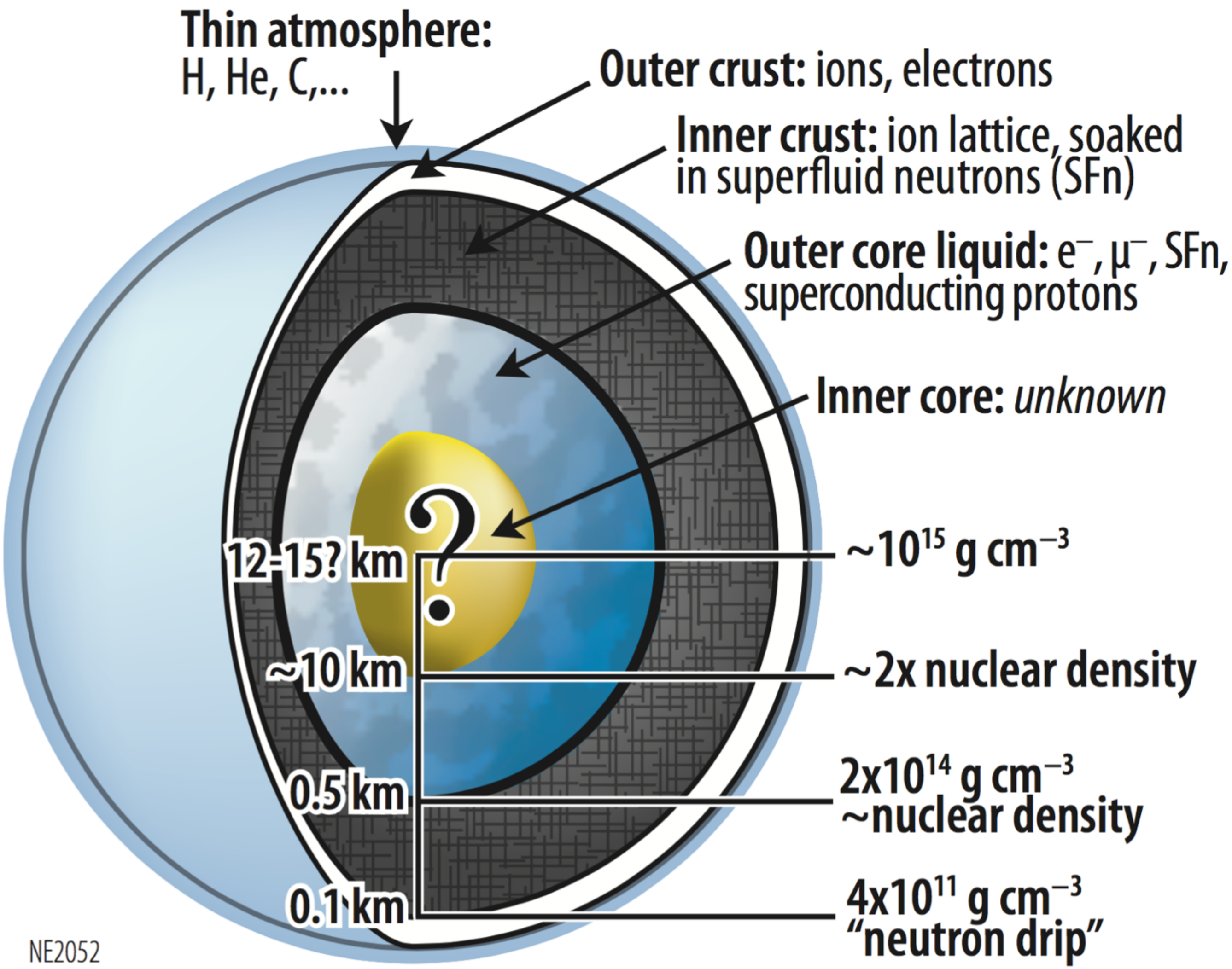
- Science
  - Why neutron stars?
  - NICER's objectives
  - Focus on key science: modeling X-ray emissions
  - Early NICER results
  - Guest Observer plans
- The NICER payload
  - Design and performance
  - Launch and installation
- SEXTANT
  - History
  - Method and objectives

# Why neutron stars?



# Why neutron stars? (cont.)

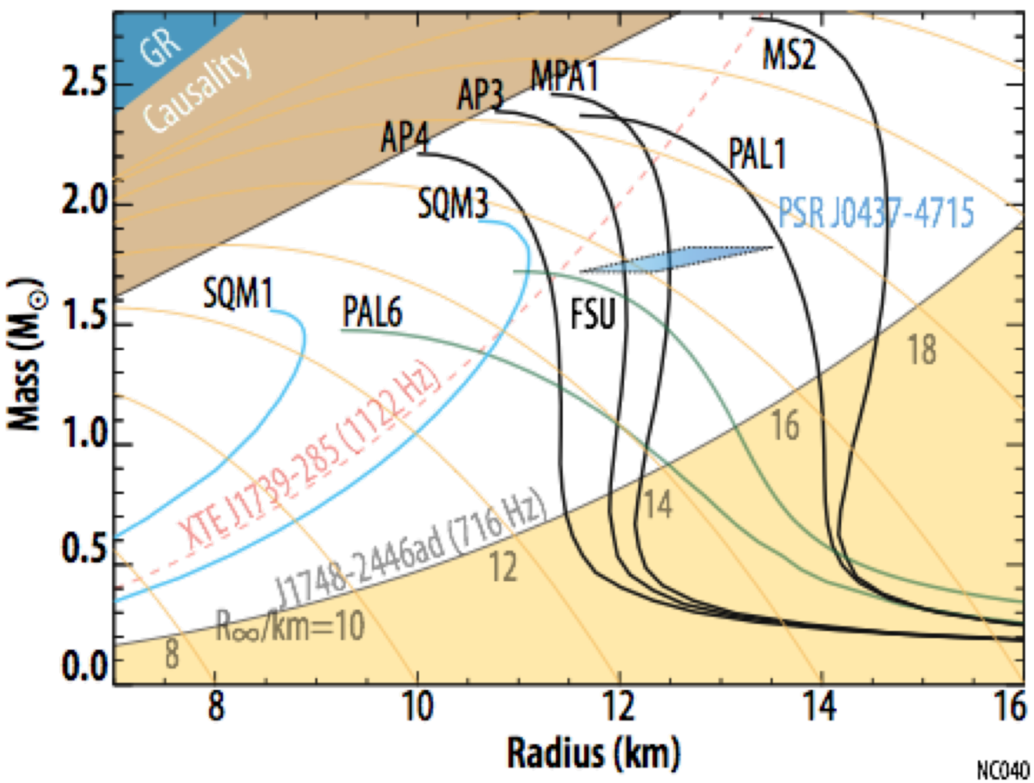
*An 80-year-old question mark*

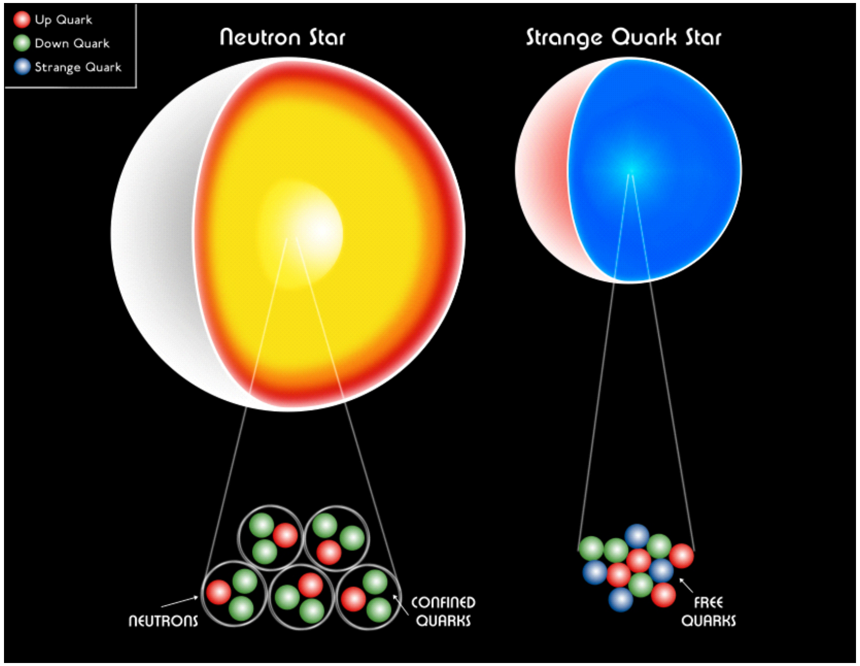


# Science objectives
# I — Neutron star structure

*Radius and mass reveal interior composition*

| Objective | Measurements |
|---|---|
| **Structure** — Uncover nature of matter within neutron stars | Neutron star radii, masses, & cooling timescales |



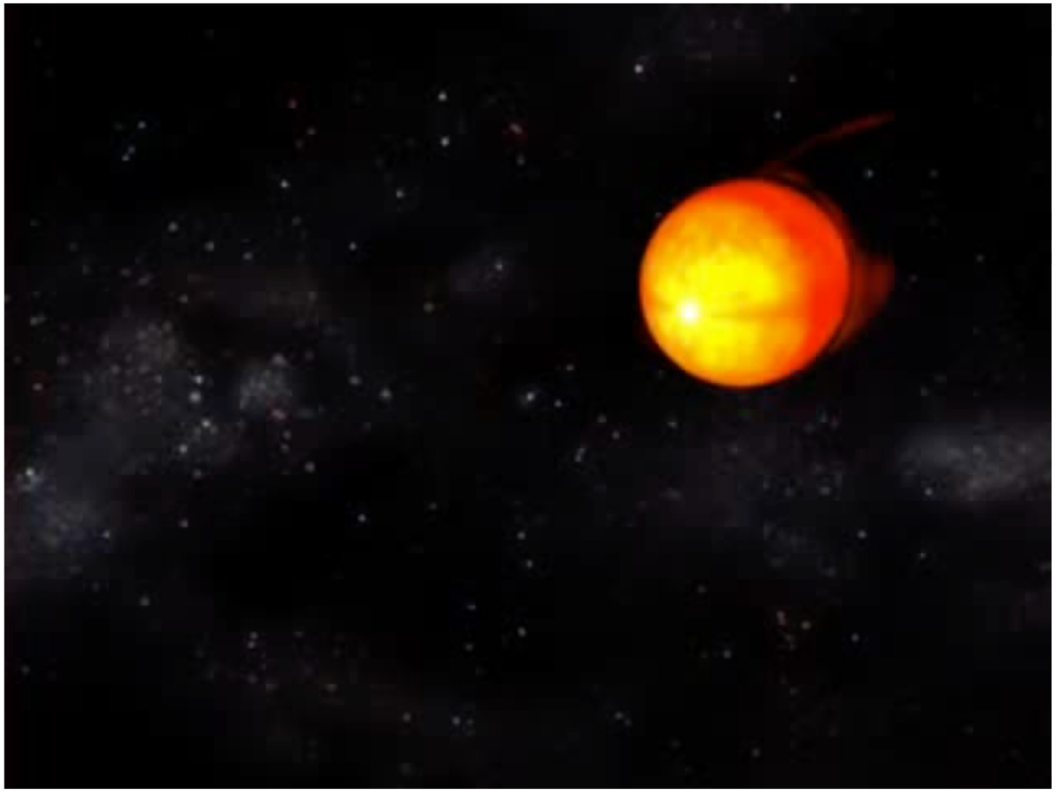

Simulations show ±5% *M-R* contours with ~ $10^6$ photons through modeling of gravitationally altered pulse lightcurves

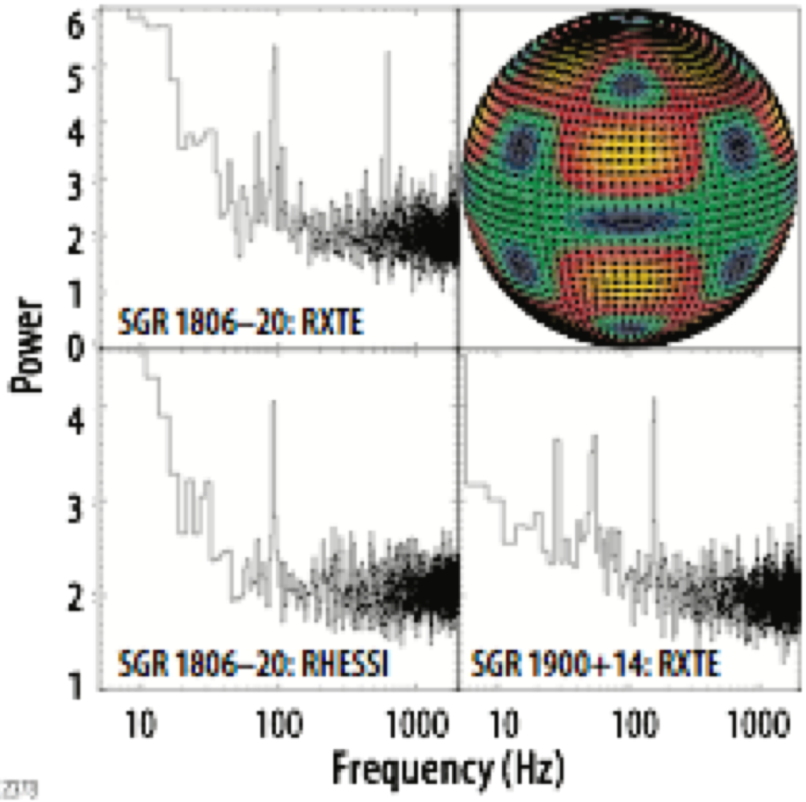
Need just 3 objects (Psaltis & Ozel 2009, Phys Rev D 80, 103003).

# Science objectives
# II — Neutron star dynamics

*Spin, accretion, and "starquake" phenomena probe crustal physics and external interactions*

| Objective | Measurements |
|---|---|
| **Dynamics** — Reveal physics of variability on many timescales | Rotational stability, outbursts, oscillations, and precession |

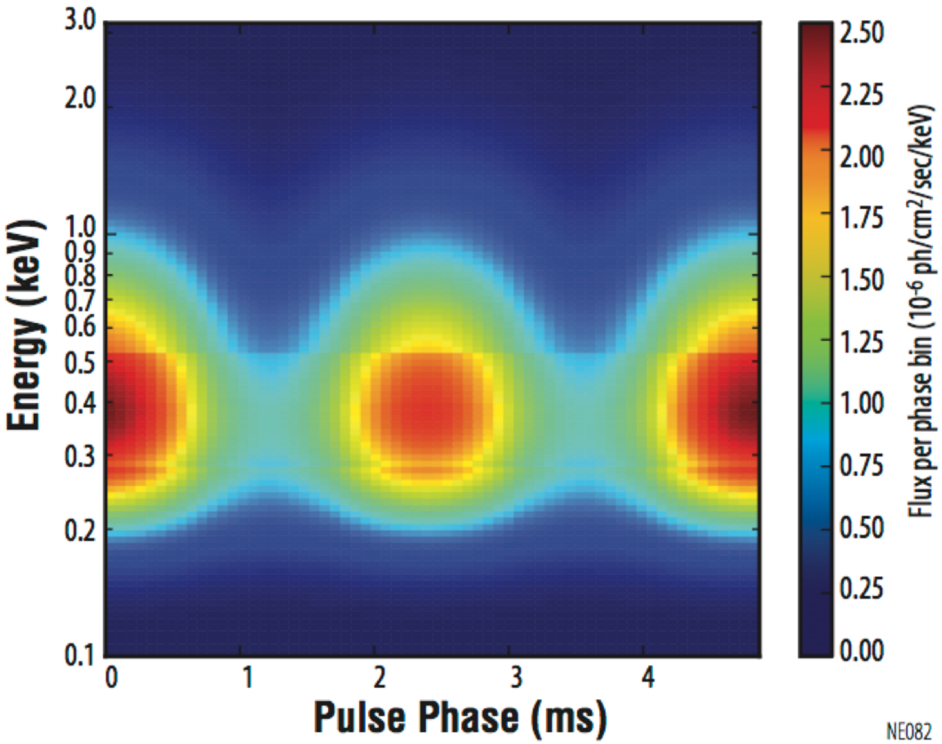


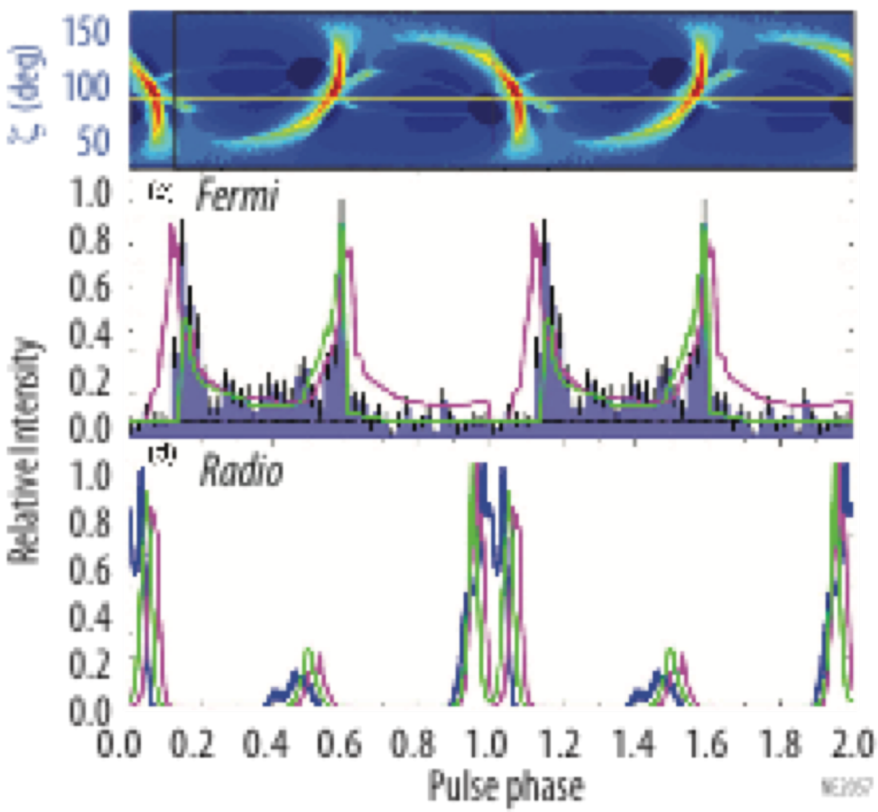


# Science objectives
# III — Neutron star energetics

*Sites & mechanisms of radiation reveal thermal, magnetic, nuclear, etc., energy stores*

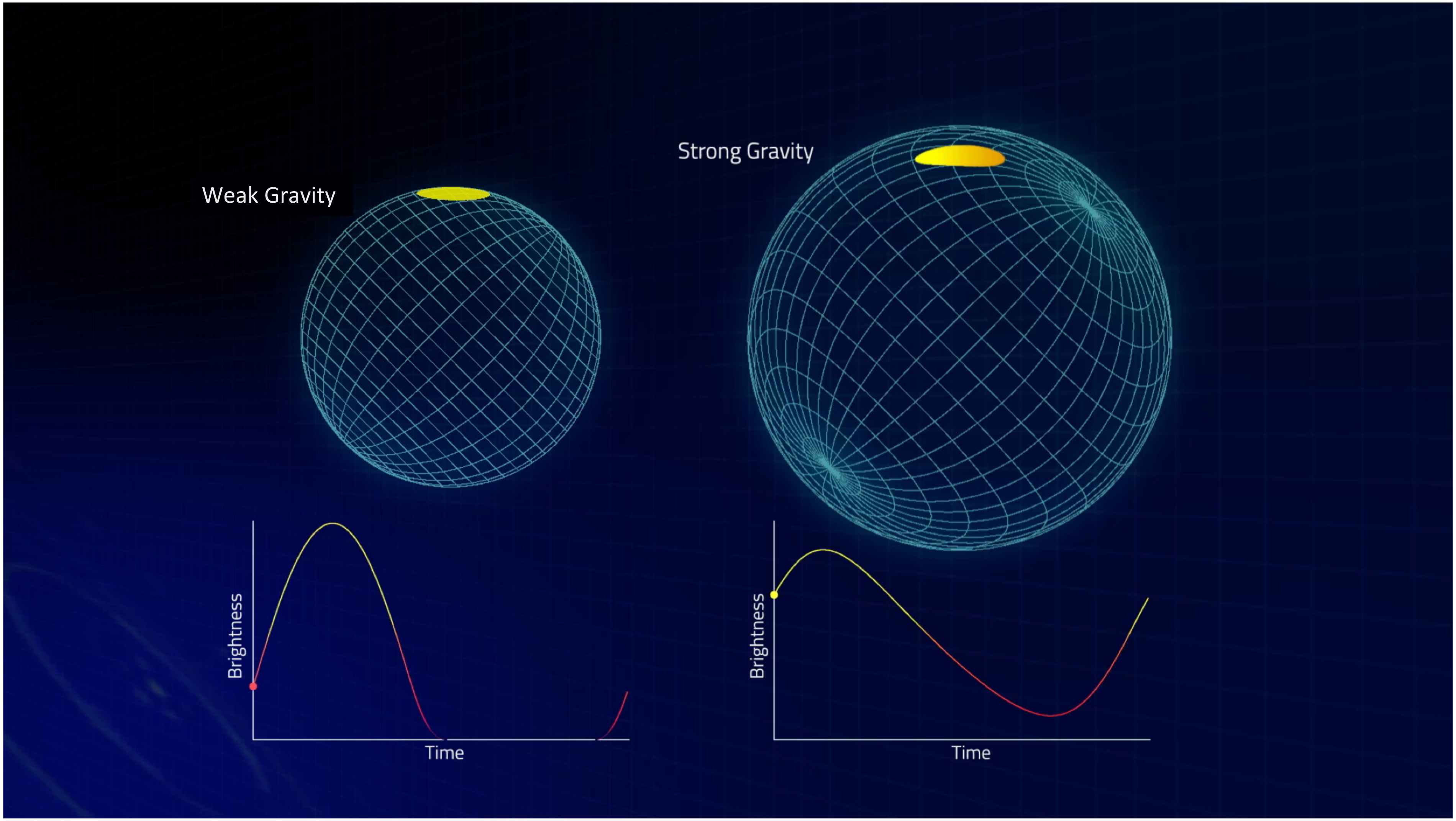
| Objective | Measurements |
|---|---|
| **Energetics** — Determine where energy is stored and extracted | Intrinsic radiation patterns, spectra, and luminosities |



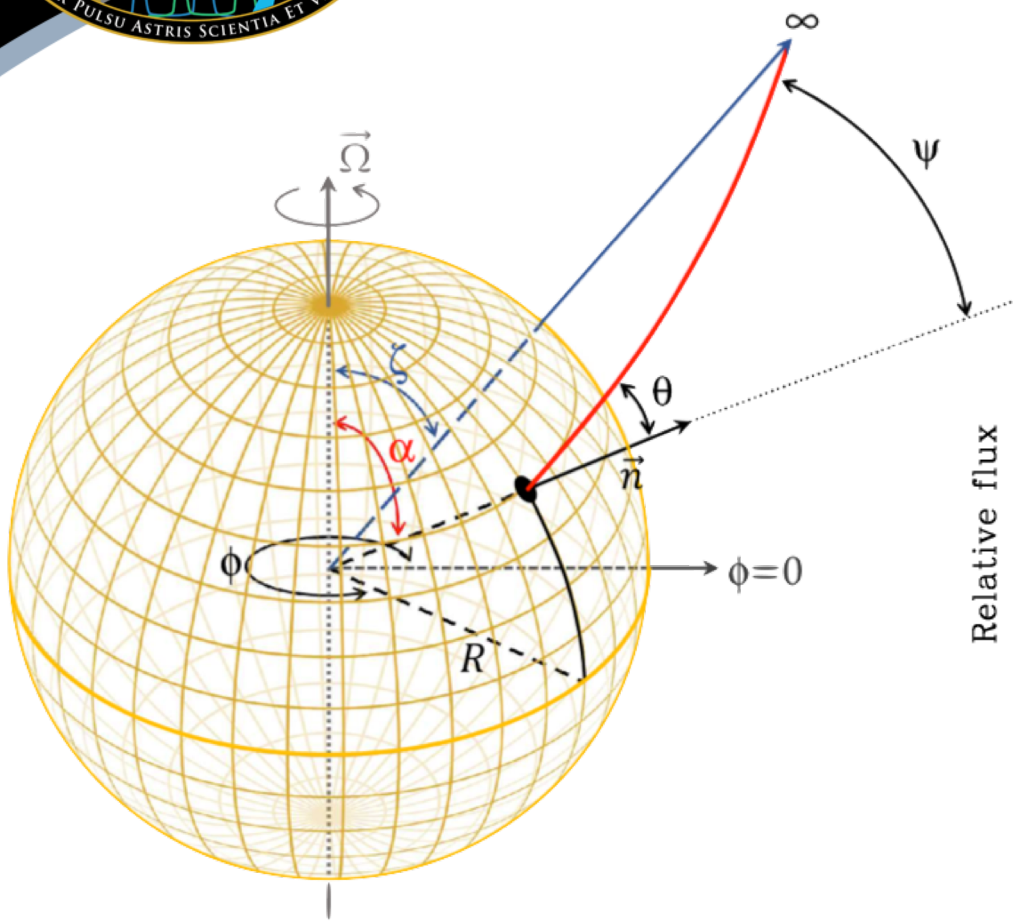



# Modeling surface emission to infer M-R

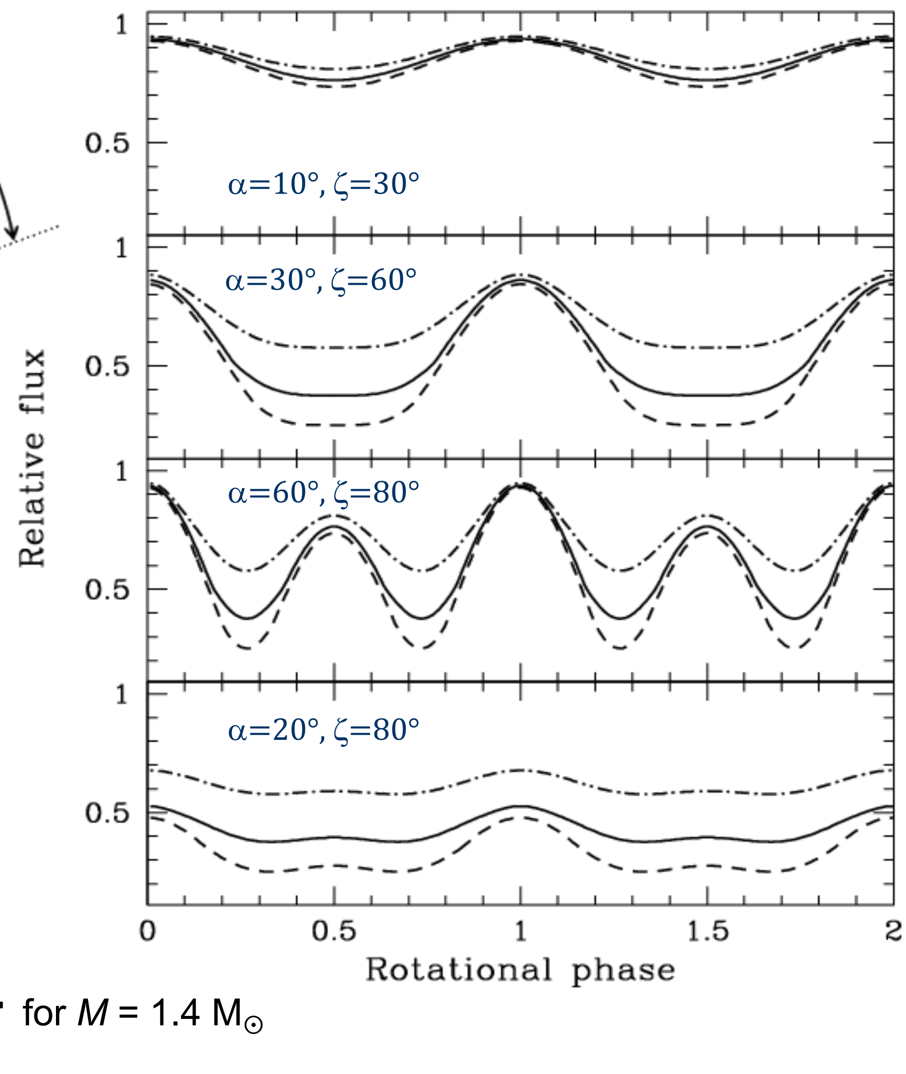
*Gravitational light-bending saves the day!*



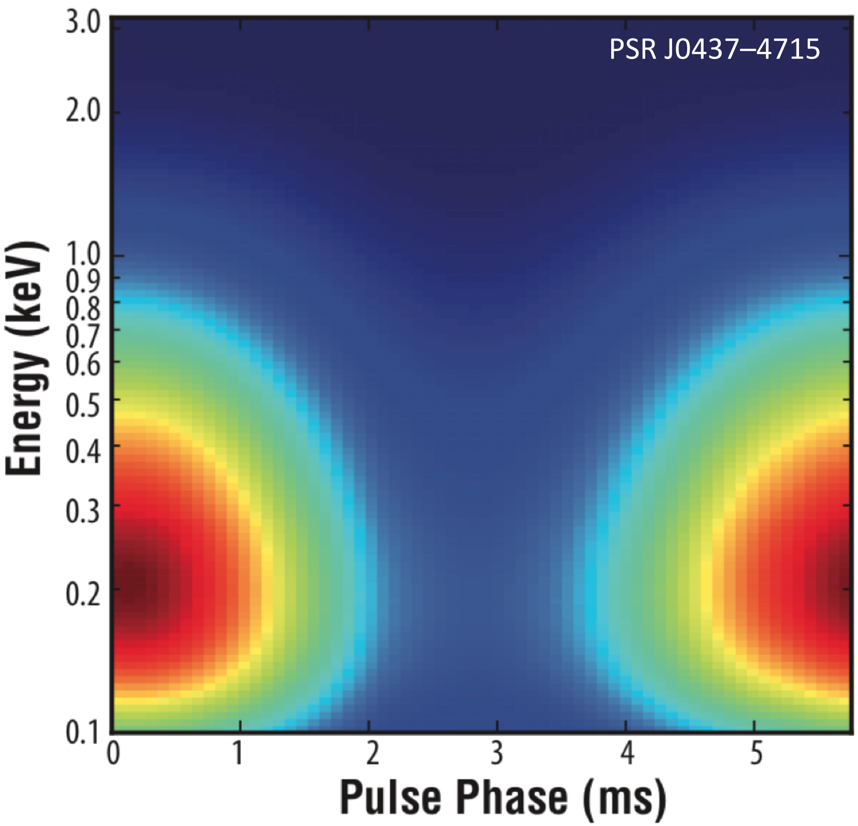
# Inferring neutron star radii through lightcurve modeling — geometry



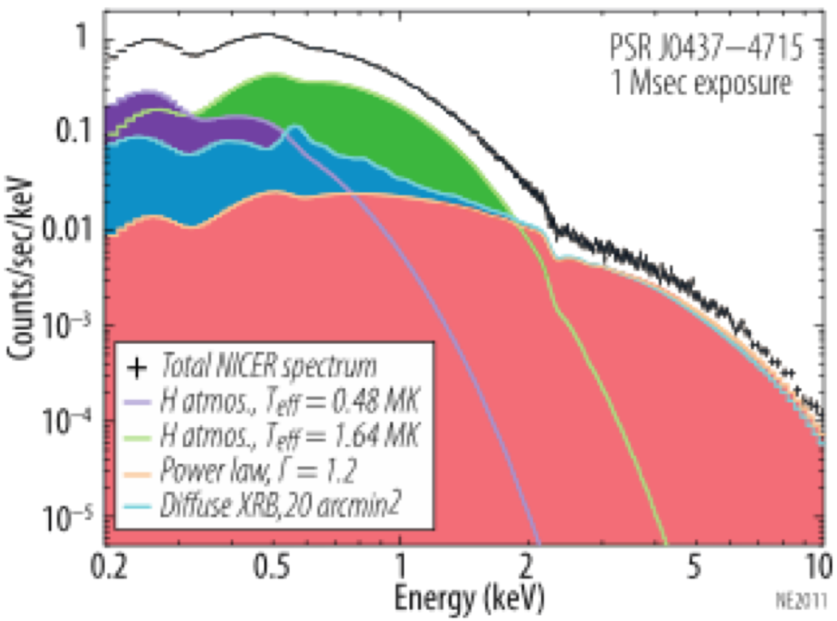

Bogdanov, Rybicki, & Grindlay, *ApJ*, 670, 668 (2007)



# Inferring neutron star radii through lightcurve modeling — spectroscopy




- NICER is most sensitive where neutron stars are brightest: ~$10^6$ K thermal emission peaks in soft X-rays
- Energy resolution enables phase-resolved spectroscopy

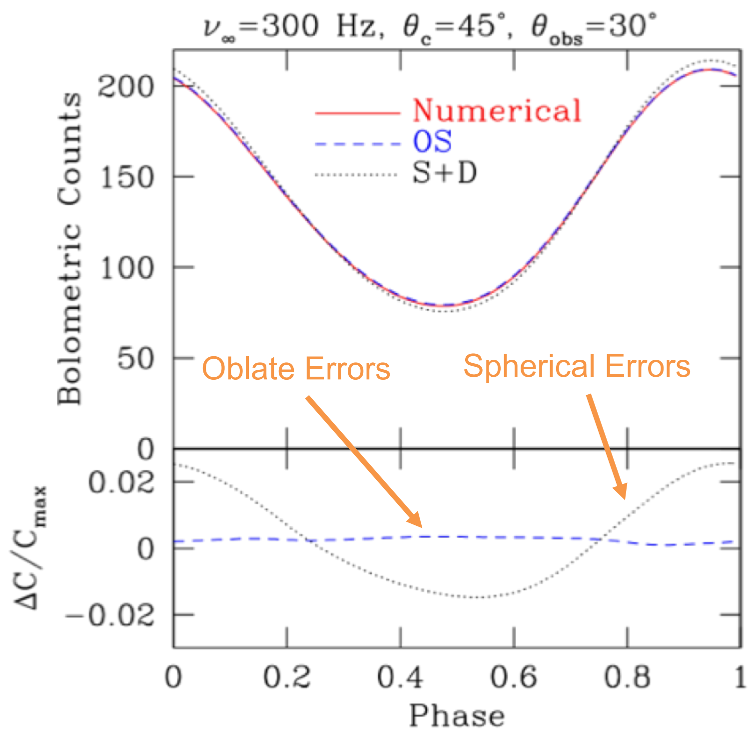


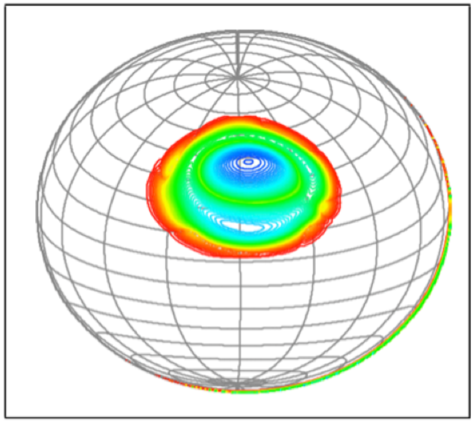

- Absolute time resolution enables coherent light curve integration over years

# Potential sources of systematics

*Known unknowns…*

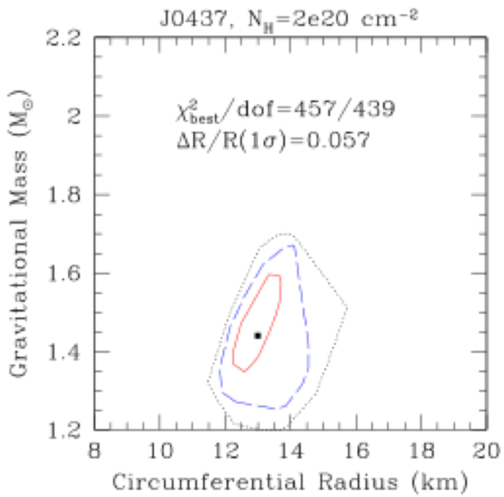
- Uncertainties in model
  - ✓ GR calculations (approximations & numerical accuracy)
  - ✓ Atmosphere model (depth of heating, hydrogen vs. helium, fully ionized?)
- Instrument calibration
  - ✓ Method does not depend on absolute flux determination
- X-ray background
  - ✓ How accurately must the background be measured?
- Unknown or weakly constrained properties of neutron star
  - ✓ Polar cap size/shape and heat distribution
  - ✓ Non-thermal emission (pulsed or unplugged?)
  - – Magnetic inclination and viewing angle
  - – Mass



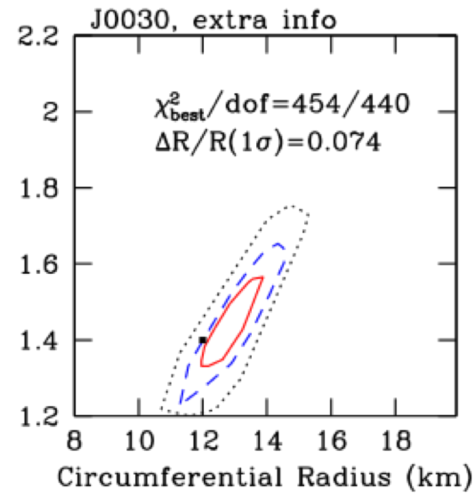
# Lightcurve modeling sim results

PSR J0437–4715, sim. $T_{exp}$ = 1 Msec

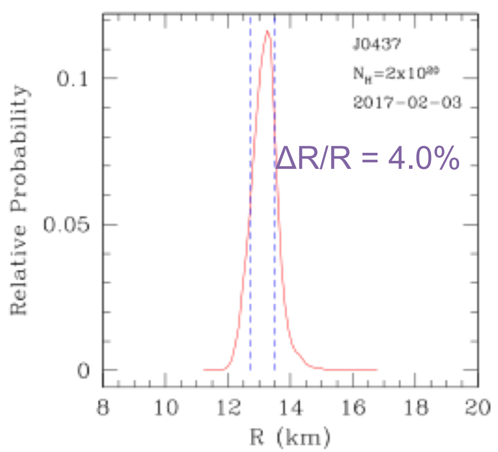


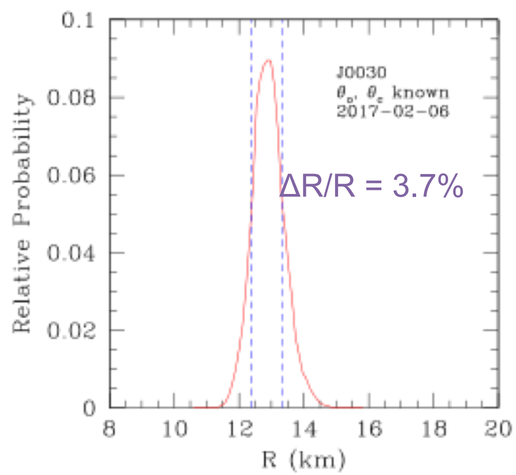

**Mass known to ±5%**

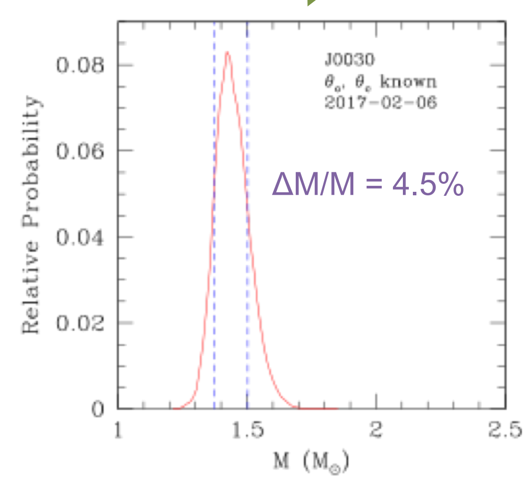
PSR J0030+0451, sim.$T_{exp}$ = 3 Msec




**Possible first-ever mass of isolated neutron star**



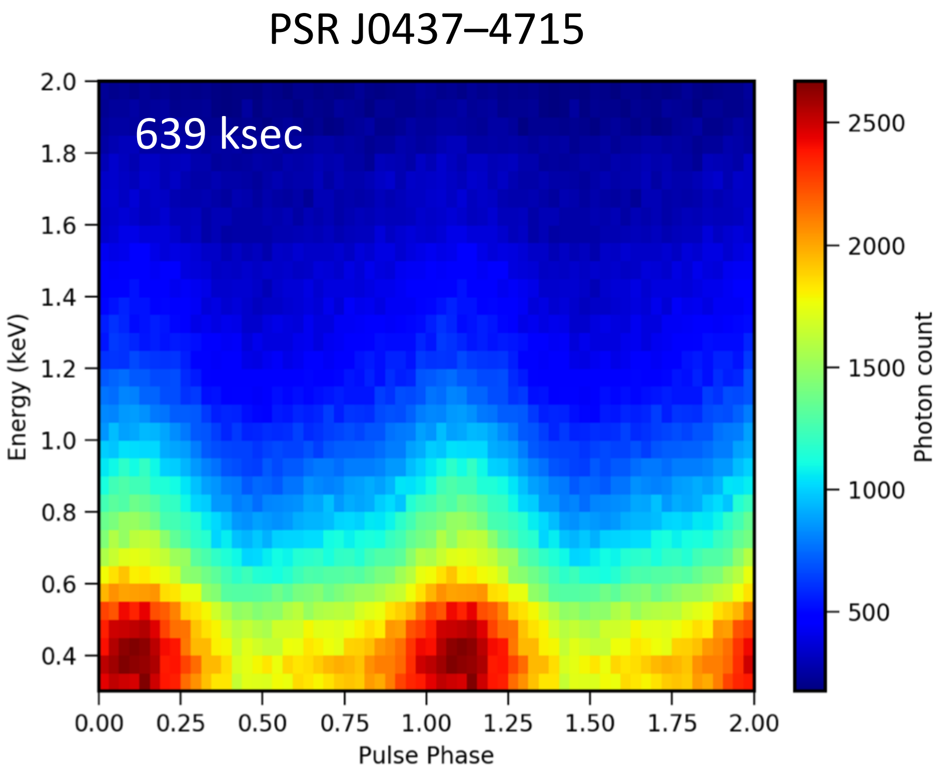



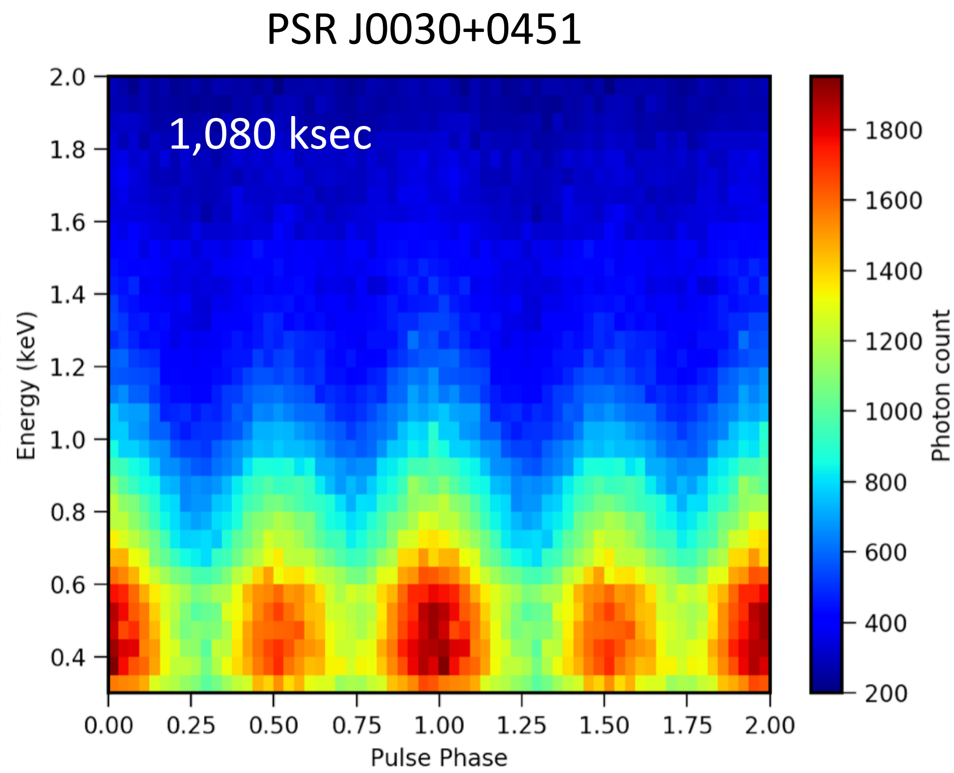




±5% in R achieved in < 1 Msec

±5% uncertainty in R achieved in 1.6 Msec

# NICER lightcurves (cont.)

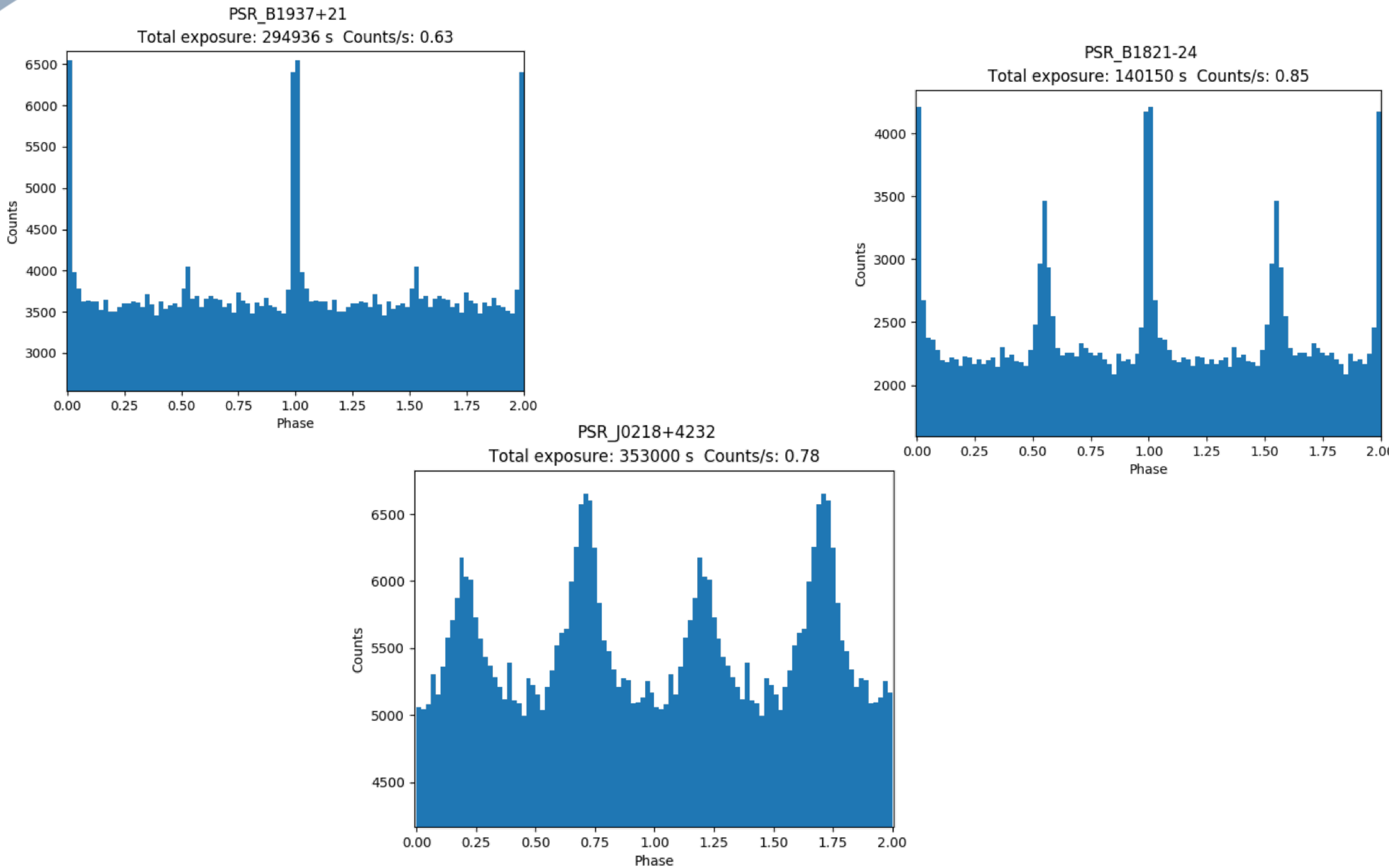



At pulse peaks, thousands of photons in joint spectral and pulse-phase bins.

# NICER timing results

## *MSPs with exceptionally high timing precision*



# Two recent Astronomer's Telegrams

## Re-detection of the accreting pulsar in Swift J1756.9–2508

### NICER Detects Pulsations from Swift J1756.9-2508

ATel #11502; ***P. M. Bult, K. C. Gendreau (NASA/GSFC), P. S. Ray (NRL), D. Altamirano (Univ. of Southampton), Z. Arzoumanian (NASA/GSFC), D. Chakrabarty (MIT), S. Guillot (IRAP, CNES), G. K. Jaisawal (DTU Space), R. M. Ludlam (Univ. of Michigan), C. B. Markwardt (NASA/GSFC), I. A. Mereminskiy (Space Research Institute, Moscow), F. Ozel (Univ. of Arizona), A. Sanna (UNICA), T. E. Strohmayer (NASA/GSFC), M. T. Wolff (NRL)***
*on **5 Apr 2018; 02:58 UT***
*Credential Certification: Deepto Chakrabarty (deepto@space.mit.edu)*

Subjects: X-ray, Neutron Star, Transient, Pulsar

Referred to by ATel #: 11505, 11523

Tweet

Following the report of a new outburst of the accreting millisecond X-ray pulsar Swift J1756.9-2508 (ATel #11497), NICER performed pointed observations starting on 2018 April 3, collecting 9.4 ks of exposure over the ~30 hours between April 3 15:18 UTC and April 4 21:01 UTC. A source is clearly detected at ~30 ct/s (1-10 keV); the background level in this band is less than 1 ct/s.

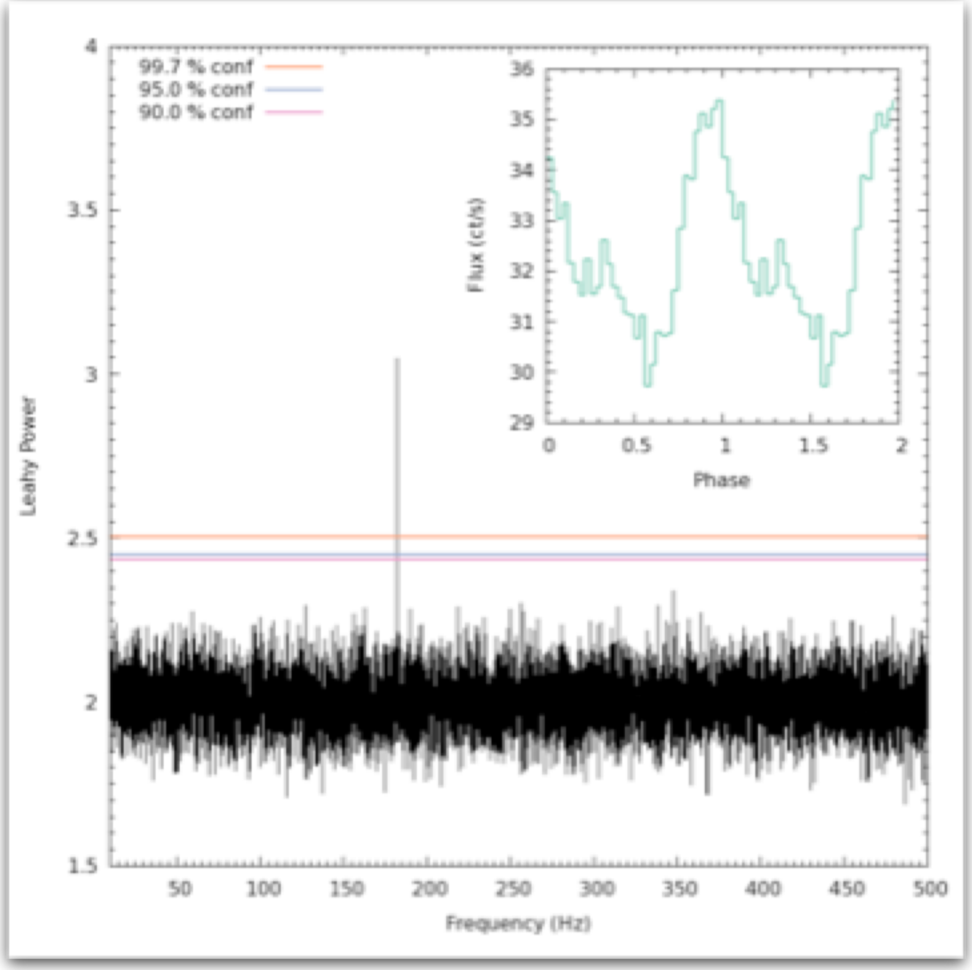
After barycenter-correcting the event times, we computed a power spectrum and detected a >5-sigma pulsation at 182.067 Hz, confirming that the active source is indeed Swift J1756.9-2508 (see Krimm et al. 2007, ApJ 668, L147, and the erratum in Krimm et al. 2009, ApJ 703, L183).

The pulsar has a known binary period of 54.7 min. Propagating the best-known orbital solution (Patruno et al. 2010, MNRAS 403, 1426) under the assumption of a constant binary period, we calculated a current-epoch time of ascending node to be T_asc = MJD 58211.0170(2) TDB. The uncertainty on this predicted reference time is less than 0.5% of the orbital period. We then optimized our trial orbital solution by scanning a grid of T_asc values in steps of 1E-5 d. We found the best solution at T_asc = MJD 58211.01736 TDB, consistent with the prediction within 2 sigma (statistical uncertainty).

Folding the data using this orbital ephemeris, we retrieved an improved pulsation detection (22 sigma) at frequency F0=182.065803(2) Hz. The pulse profile is non-sinusoidal, showing a fractional sinusoidal amplitude of 5.9% for the fundamental and 3.4% for the first overtone, both measured in the 1-10 keV band. The shape of the pulse profile is similar to those shown in Figure 1 of Patruno et al. (2010), albeit in a somewhat softer, overlapping energy band. A more detailed analysis is underway.

The X-ray spectrum is consistent with an absorbed disk-blackbody plus power-law model (red. chi^2 = 1.18 for 840 d.o.f). We measured an absorption column density of N_H = 6.4(2)E22 cm^-2, a disk temperature of kT = 0.17(1) keV, and a power-law photon index of Gamma = 2.04(3). There is no evidence of an Fe line feature near ~6.4 keV in the spectrum. The unabsorbed 1-10 keV flux is 1.3e-9 erg/s/cm^2. All values are consistent with those of the previous outbursts, and suggest that the source is in a typical atoll-type island (hard) spectral state.

Further NICER observations of this source are underway. Additional multiwavelength follow-up is encouraged.



# Two recent Astronomer's Telegrams (cont.)

## Discovery of the accreting pulsar in IGR J17379–3747

### NICER discovers millisecond pulsations from the neutron star LMXB IGR J17379-3747

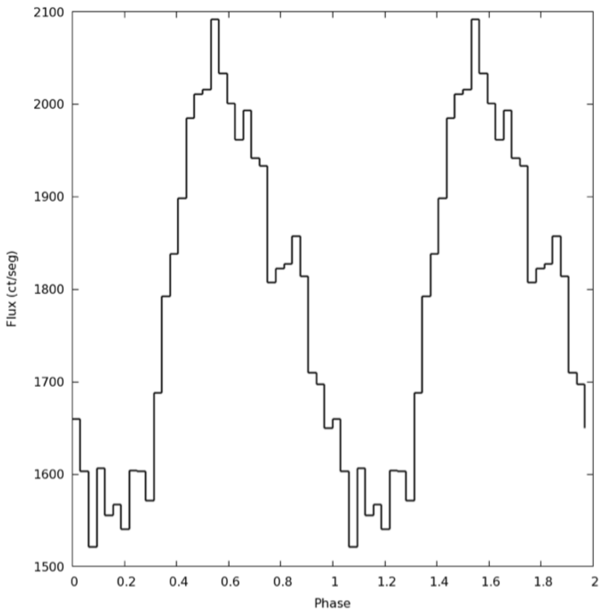
ATel #11507; ***T. E. Strohmayer (NASA/GSFC), P. S. Ray (NRL), K. C. Gendreau (NASA/GSFC), P. M. Bult (NASA/GSFC), S. Guillot (IRAP, CNES), S. Mahmoodifar (NASA/GSFC), G. K. Jaisawal (DTU Space), Z. Arzoumanian (NASA/GSFC), D. Altamirano (Univ. of Southampton), S. Bogdanov (Columbia), D. Chakrabarty (MIT), T. Enoto (Kyoto Univ.), C. B. Markwardt (NASA/GSFC), F. Ozel (Univ. of Arizona), S. M. Ransom (NRAO)***
*on **6 Apr 2018; 02:22 UT***
*Credential Certification: Tod Strohmayer (tod.strohmayer@nasa.gov)*

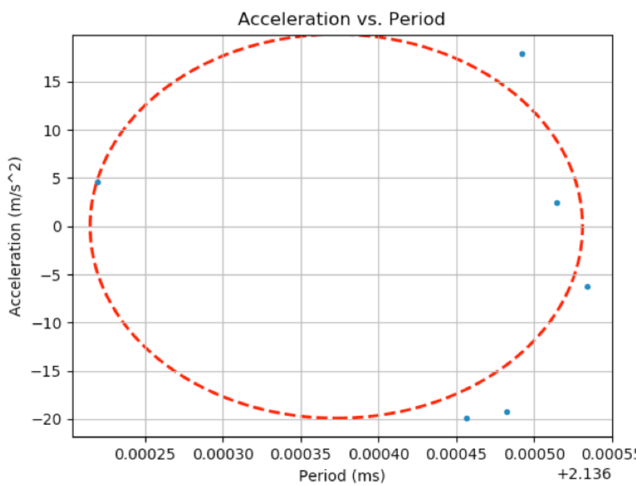
Subjects: X-ray, Request for Observations, Binary, Neutron Star, Pulsar

Referred to by ATel #: 11520

Tweet

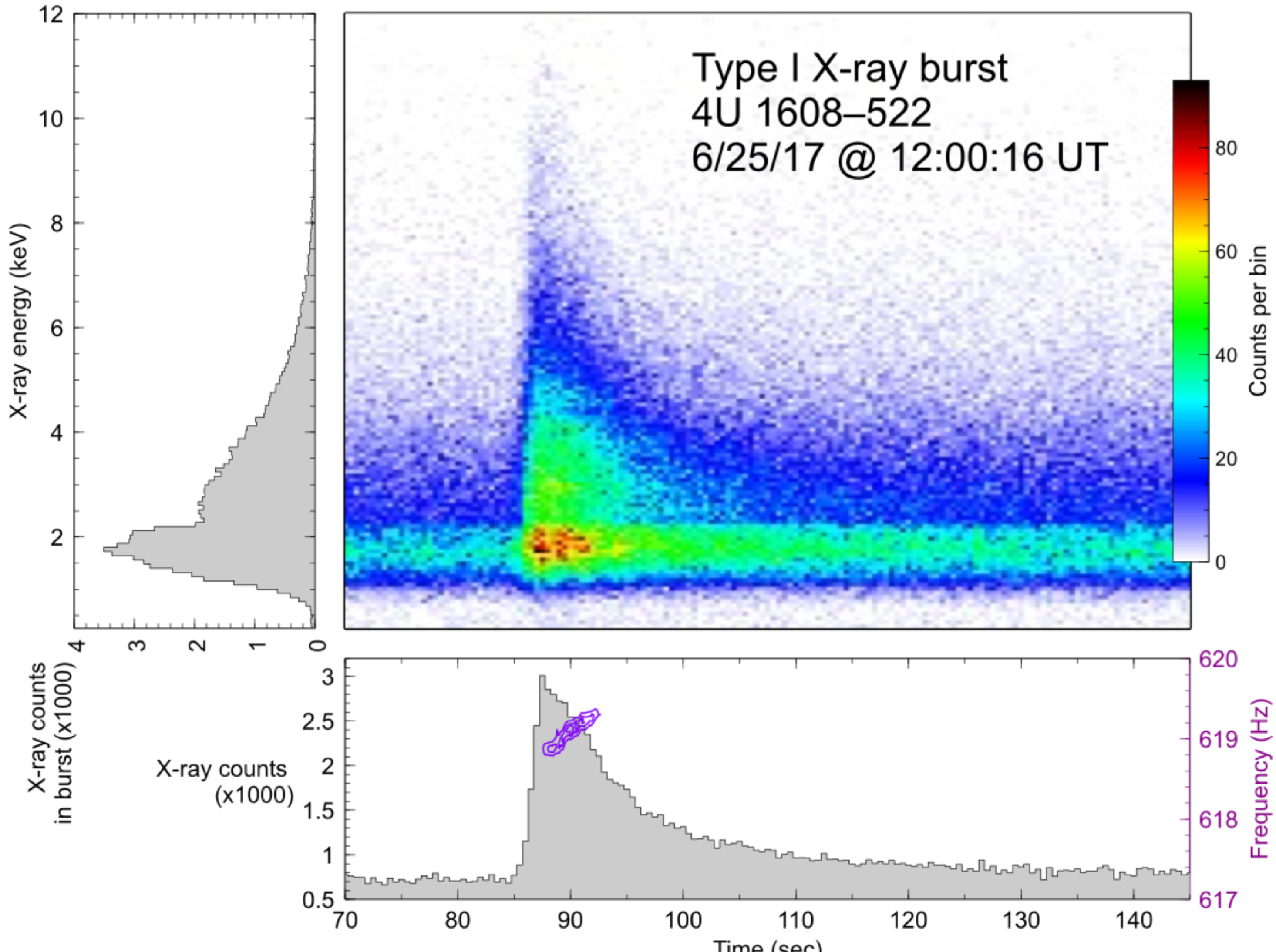
Following a 2018 March 19 MAXI alert of a new outburst of the neutron star low-mass X-ray binary IGR J17379-3747 (ATel #11447), NICER has observed the source daily since 2018 March 29. From that date onward, the mean count rates detected each day through April 1 were 12.9, 11.0, 8.7, and 4.7 ct/s (0.5-12 keV), respectively. The background count rate in this band is less than 1 ct/s. After applying barycenter corrections to the event times using the radio position reported in ATel #11487, we computed a combined power spectrum of the full ~9 ks collected exposure and detected a clear pulsation (> 7 sigma significance for a single trial) at a frequency of 468.05 Hz. The data consist of 11 segments of varying uninterrupted exposure between 500 s and 1000 s duration. We searched these segments for pulsations individually using the PRESTO acceleration search code. We detected a power-spectrum excess near 468.05 Hz in seven of those segments (at a significance ranging from 6 to 8 sigma in each segment, with frequencies ranging from 468.05 to 468.12 Hz). Fitting the observed frequency modulation with a circular orbit model yielded an excellent fit, with an orbital period of 1.88 hrs and a minimum companion mass of 0.055 Msun (assuming a 1.4 Msun neutron star). The barycentric pulsar spin frequency is 468.0832 Hz. We extracted a 0.5-10 keV spectrum for each day, and find they are all consistent with an absorbed power-law model. However, adding a blackbody component significantly improves the fits (reduced Chi^2 = 0.97 for 1278 d.o.f.). The blackbody temperature decreases from 0.52+/-0.06 keV to 0.39+/-0.03 keV as the flux declines. At the same time, the power-law component softens slightly, with the photon index evolving from 2.1+/-0.1 to 2.4+/-0.1. The measured hydrogen column density is N_H=(0.7+/-0.1)e22 cm^-2, consistent with a previously reported value (ATel #1714), but significantly lower than the most recently reported value (ATel #11487). The unabsorbed flux decreases from 7.4e-11 ergs/cm^2/s (2018 March 29) to 2.5e-11 ergs/cm^2/s (2018 April 1). Our pulsation detection conclusively identifies IGR J17379-3747 as an accreting millisecond X-ray pulsar. NICER monitoring of the source continues. Given its rapidly declining X-ray flux, prompt follow up at other wavelengths is encouraged.



# Early NICER burst results (cont.)

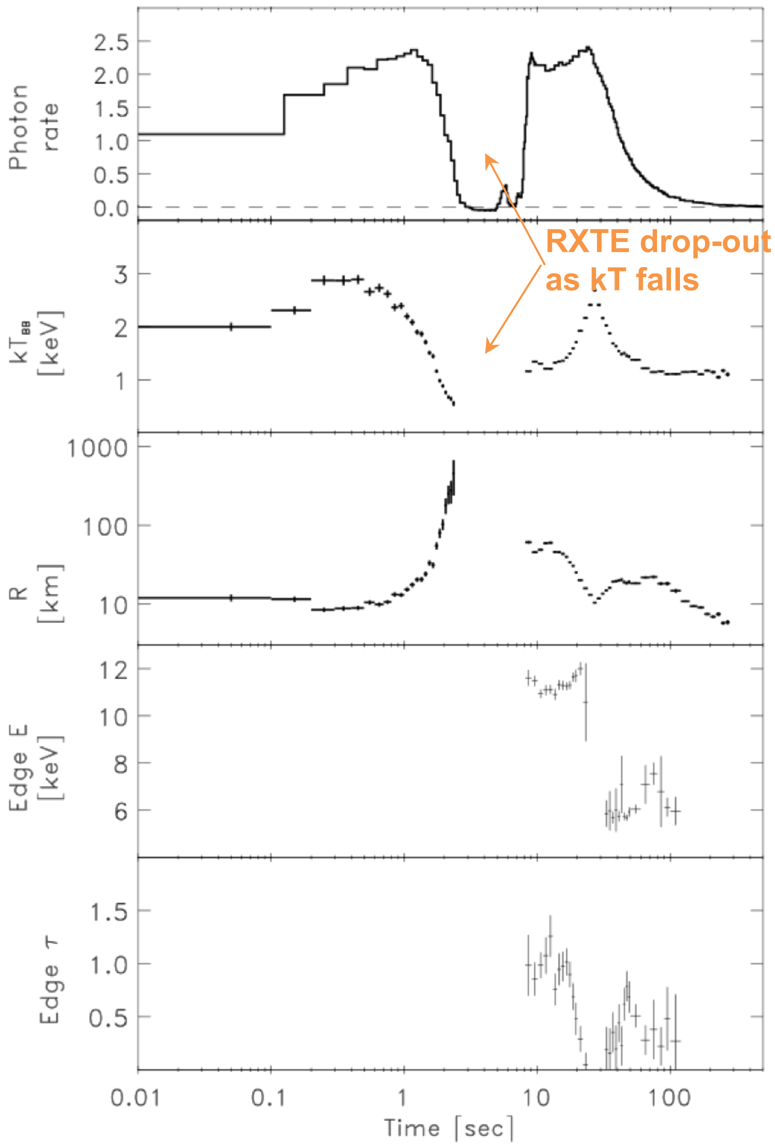
*619 Hz burst oscillations*



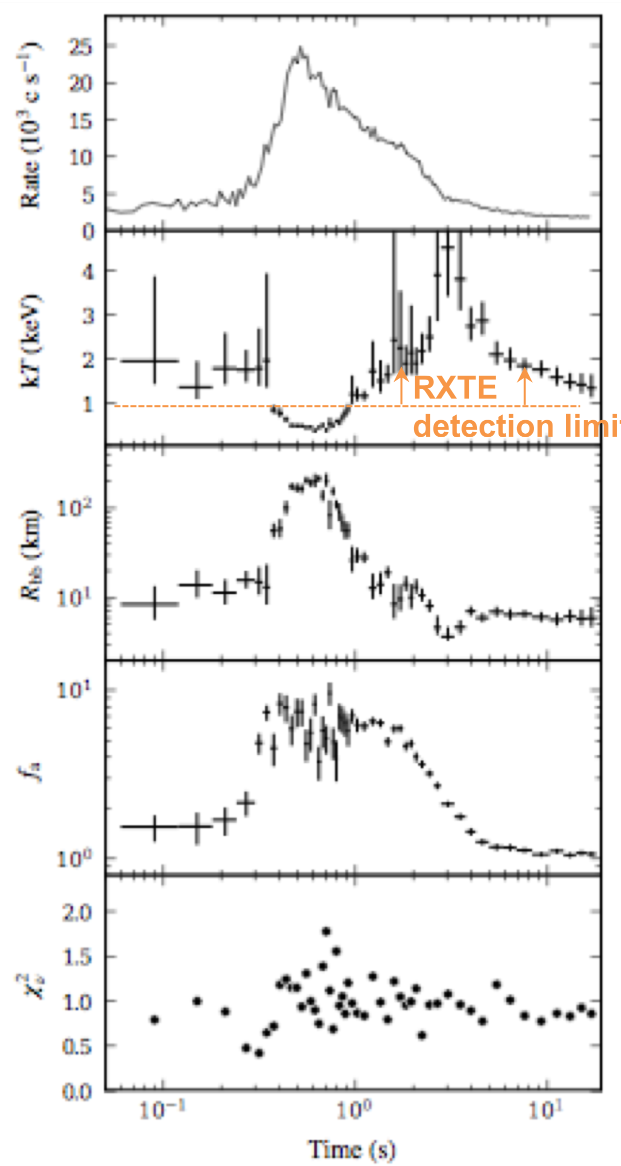
# Early NICER burst results

*Photospheric radius "super expansion" evolution*

4U 1722–30 with RXTE

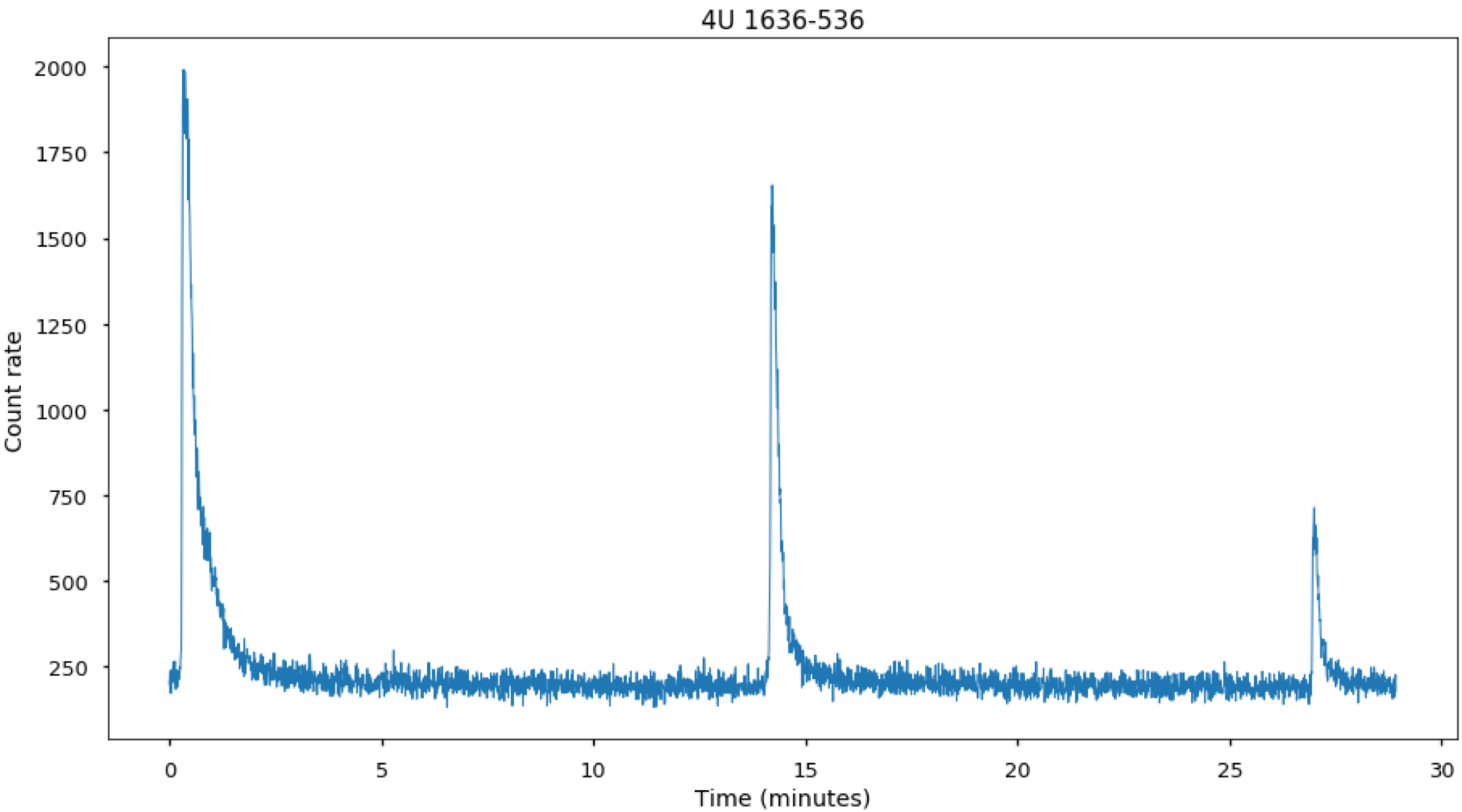



4U 1820–30 with NICER



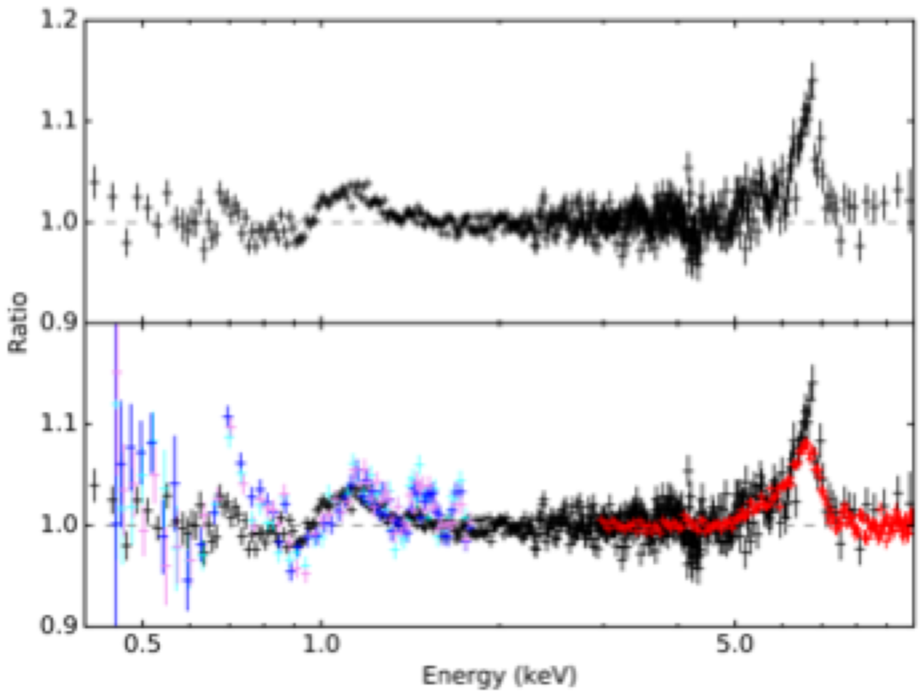
# Short recurrence-time bursts

*Just 13 min apart, too soon for the atmosphere to recover…*

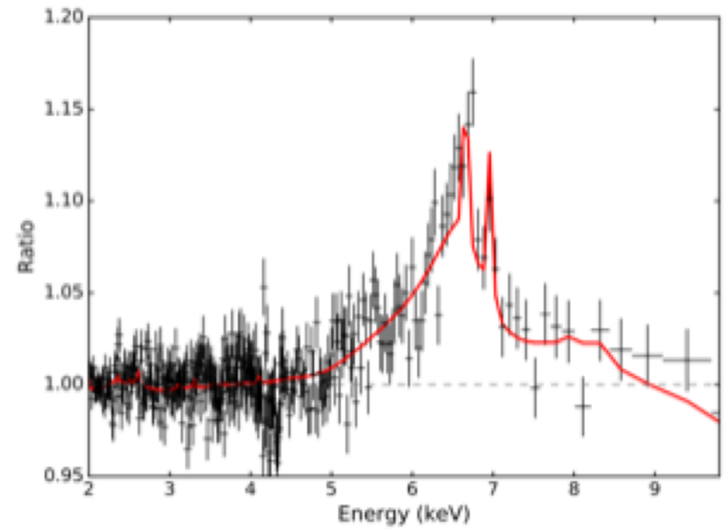


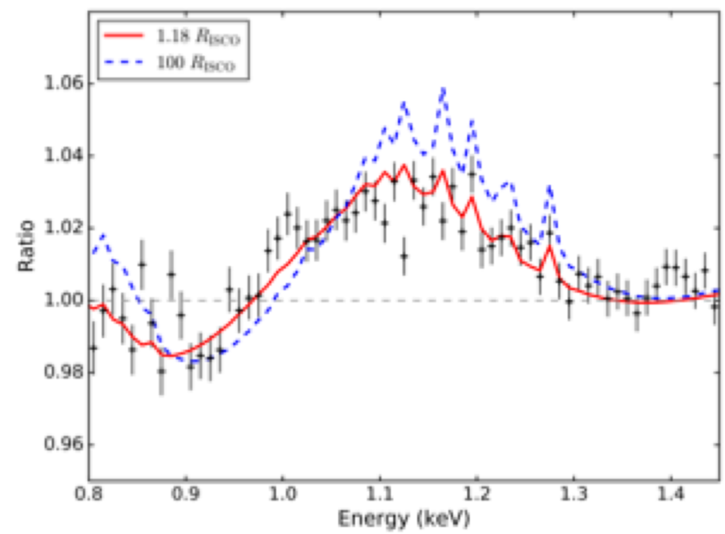
# Iron "reflection" in Serpens X-1

*Inner edge of accretion disk is upper limit on NS radius*




NICER (black), NuSTAR (red), XMM-Newton (blue/purple)

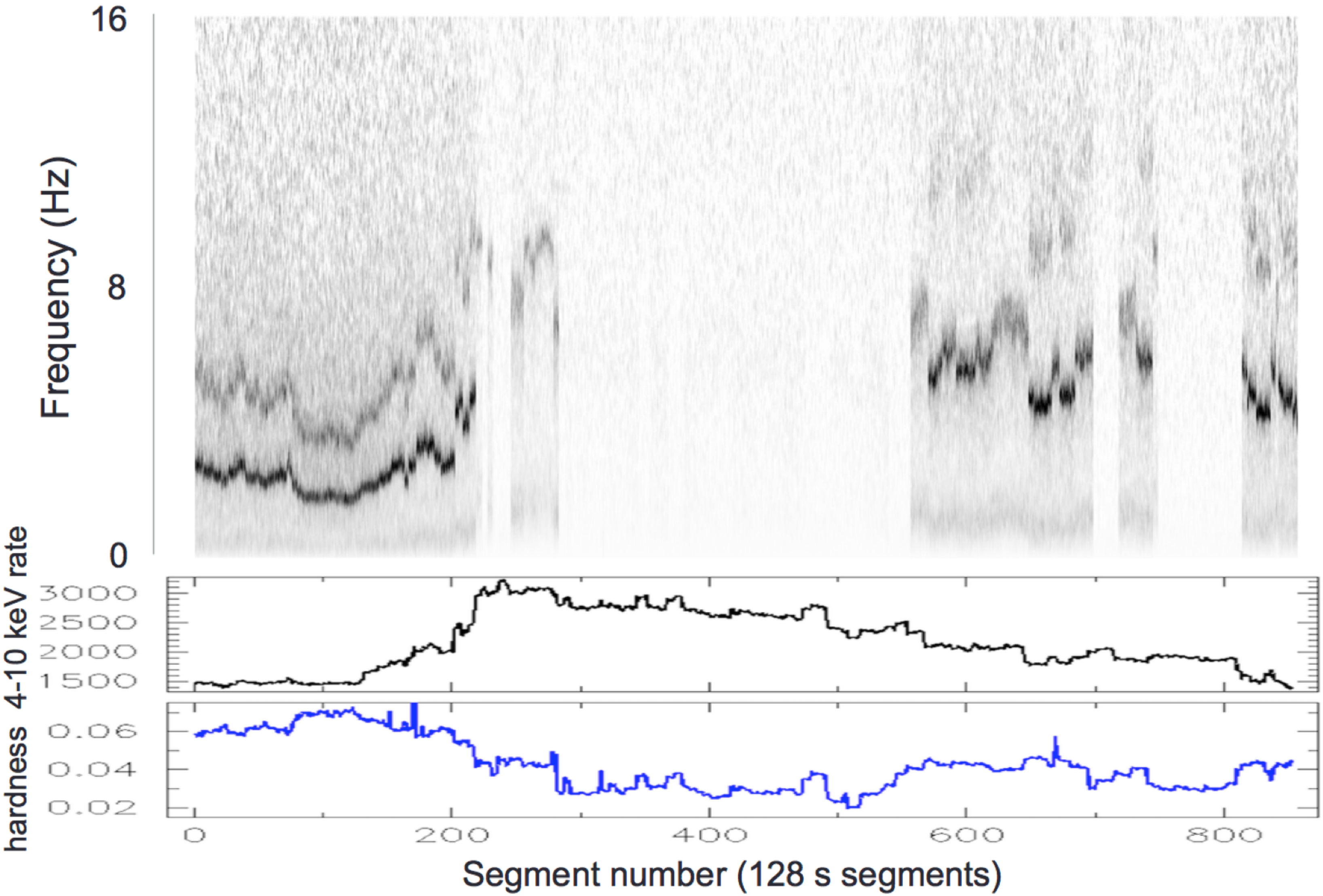



Reflection lines are shaped by Doppler and relativistic effects due to the proximity to the neutron star. In a 4.5 ksec observation the best-fit reflection models suggest that the inner disk extends close to an inner radius of between 12.4 and 19.8 km.

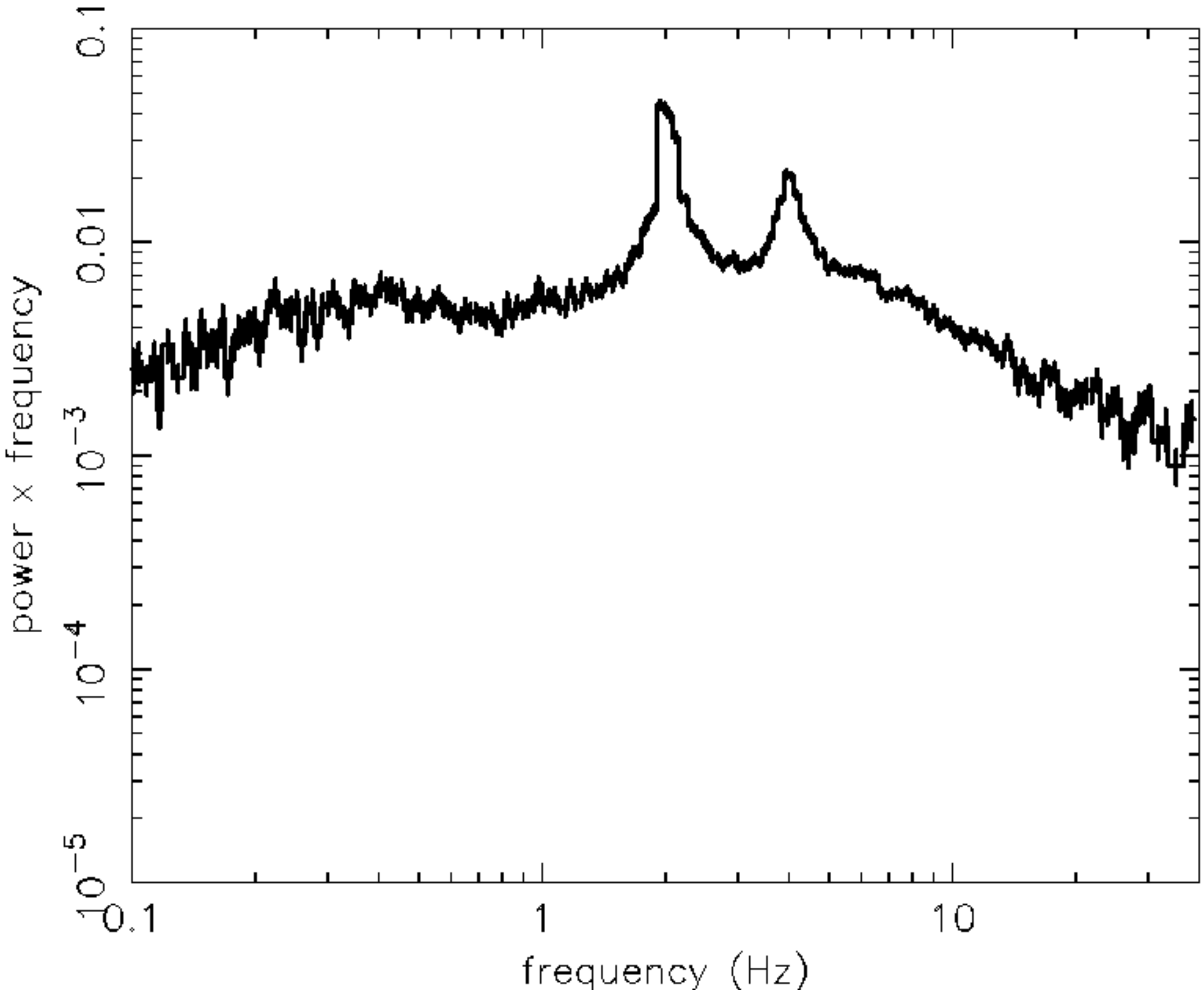
# NICER Observatory Science results

*Black hole transient in outburst: MAXI J1535–571*



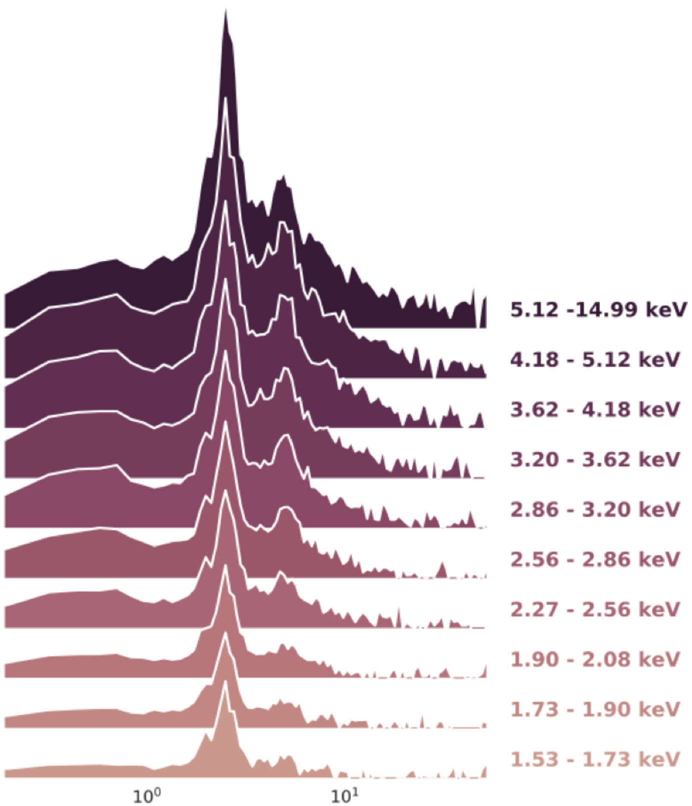
# NICER Observatory Science results (cont.)

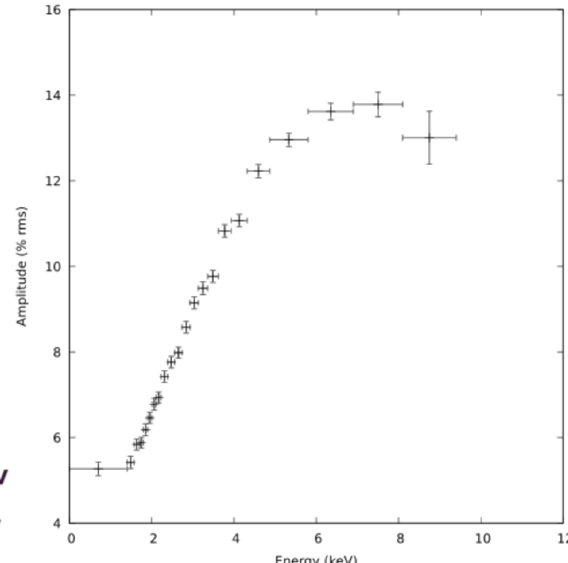
## MAXI J1535's marching QPOs

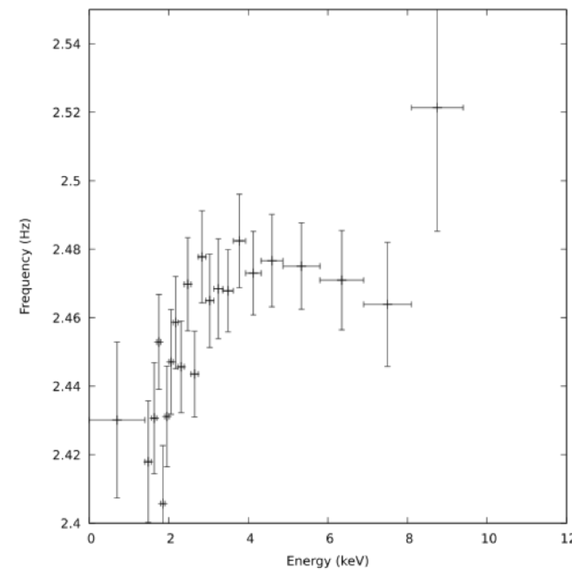


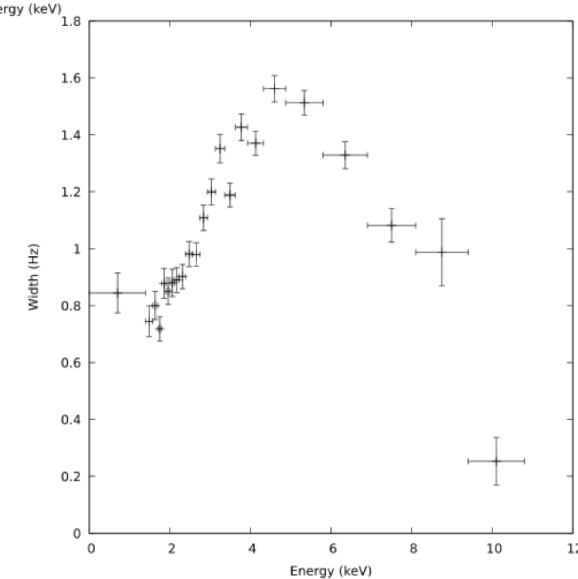
# Early black-hole binary results (cont.)

## *Energy dependence of low-frequency QPOs in MAXI J1535-571*



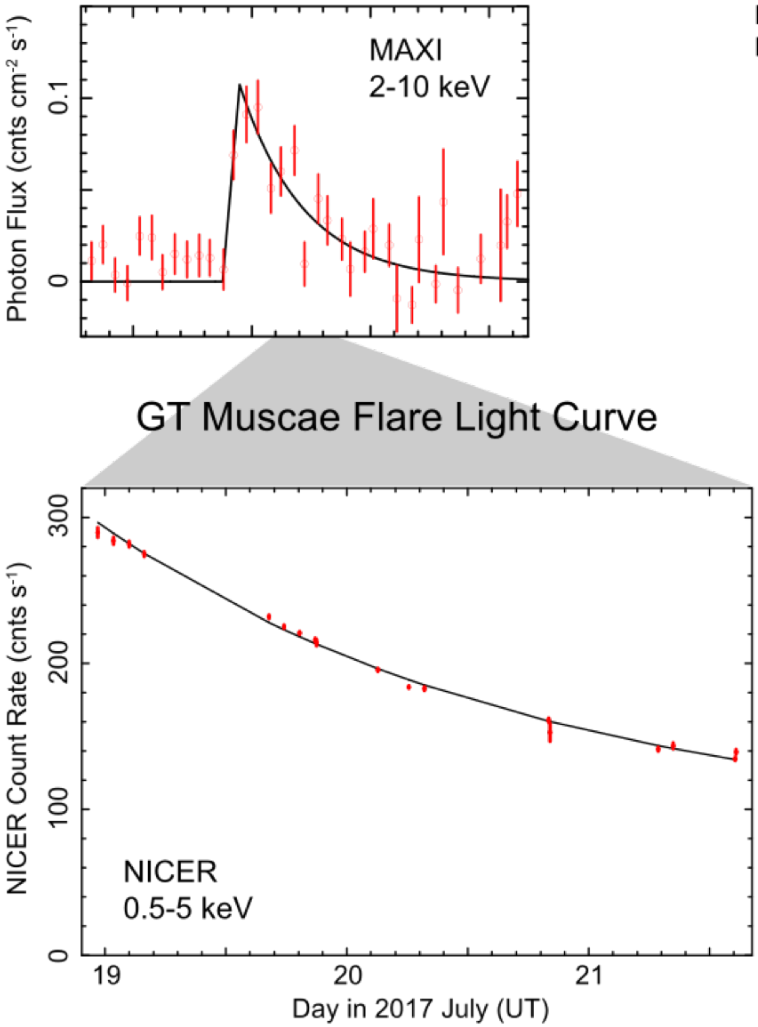



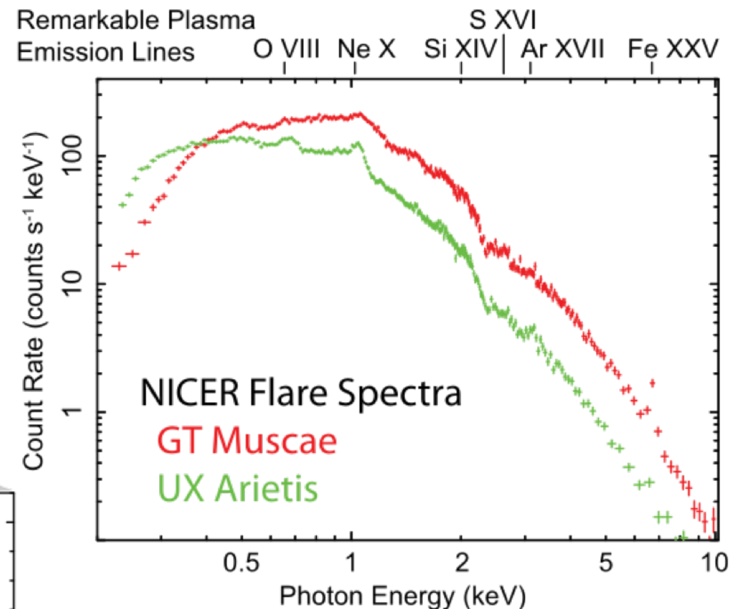



# NICER Observatory Science results (cont.)

*Two stellar flare ToOs triggered by MAXI: GT Mus and UX Ari*



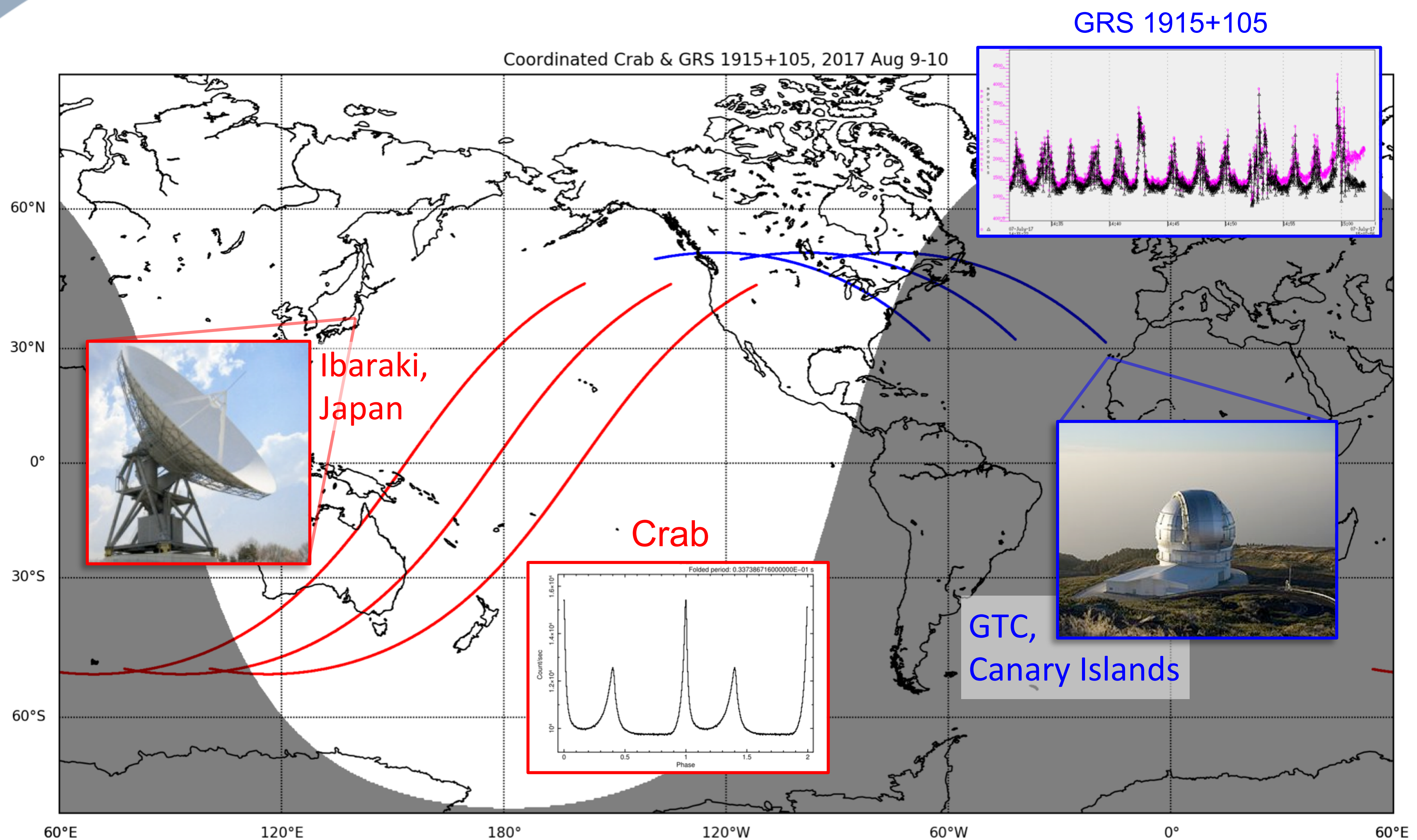




Constraints on elemental composition of flaring plasma, and stellar magnetic structure, on previously inaccessible timescales

**MAXI has just been extended for another 3 years!**

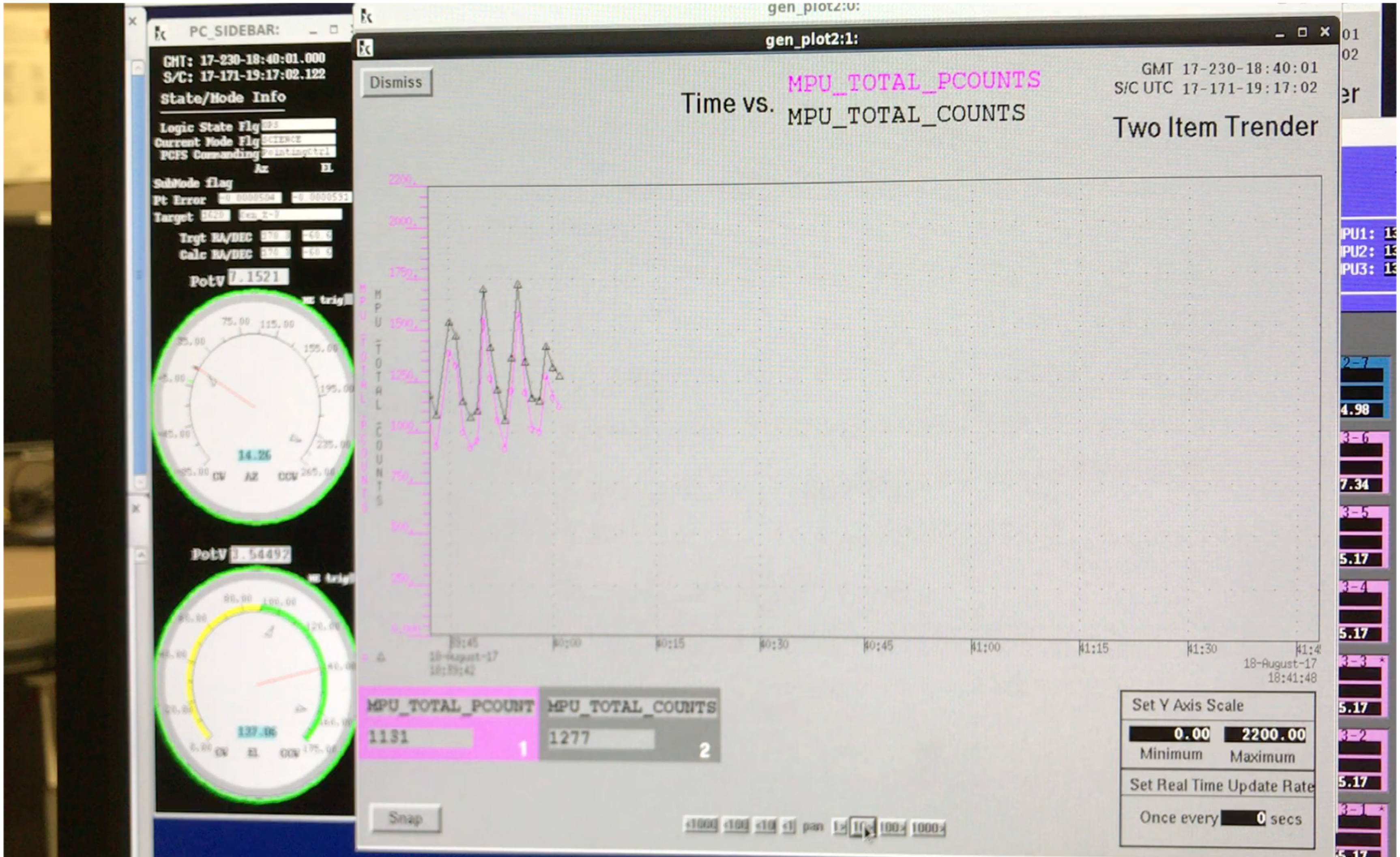
# Coordination across facilities and wavelengths

*Two targets, two ground-based telescopes, three successive ISS orbits*



# Live ISS telemetry ~80% of the time

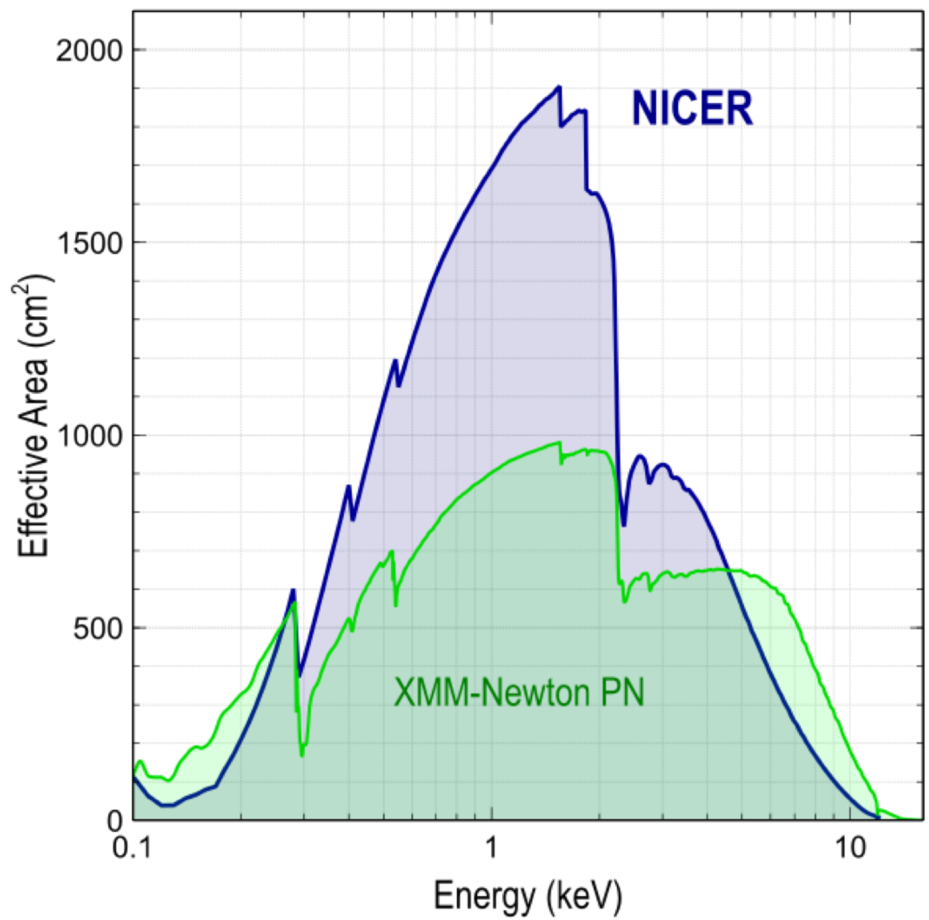
*Cen X-3 pulsations in real time*



# X-ray Timing Instrument (XTI) capabilities

*A novel combination of sensitivity, timing, and energy resolution*

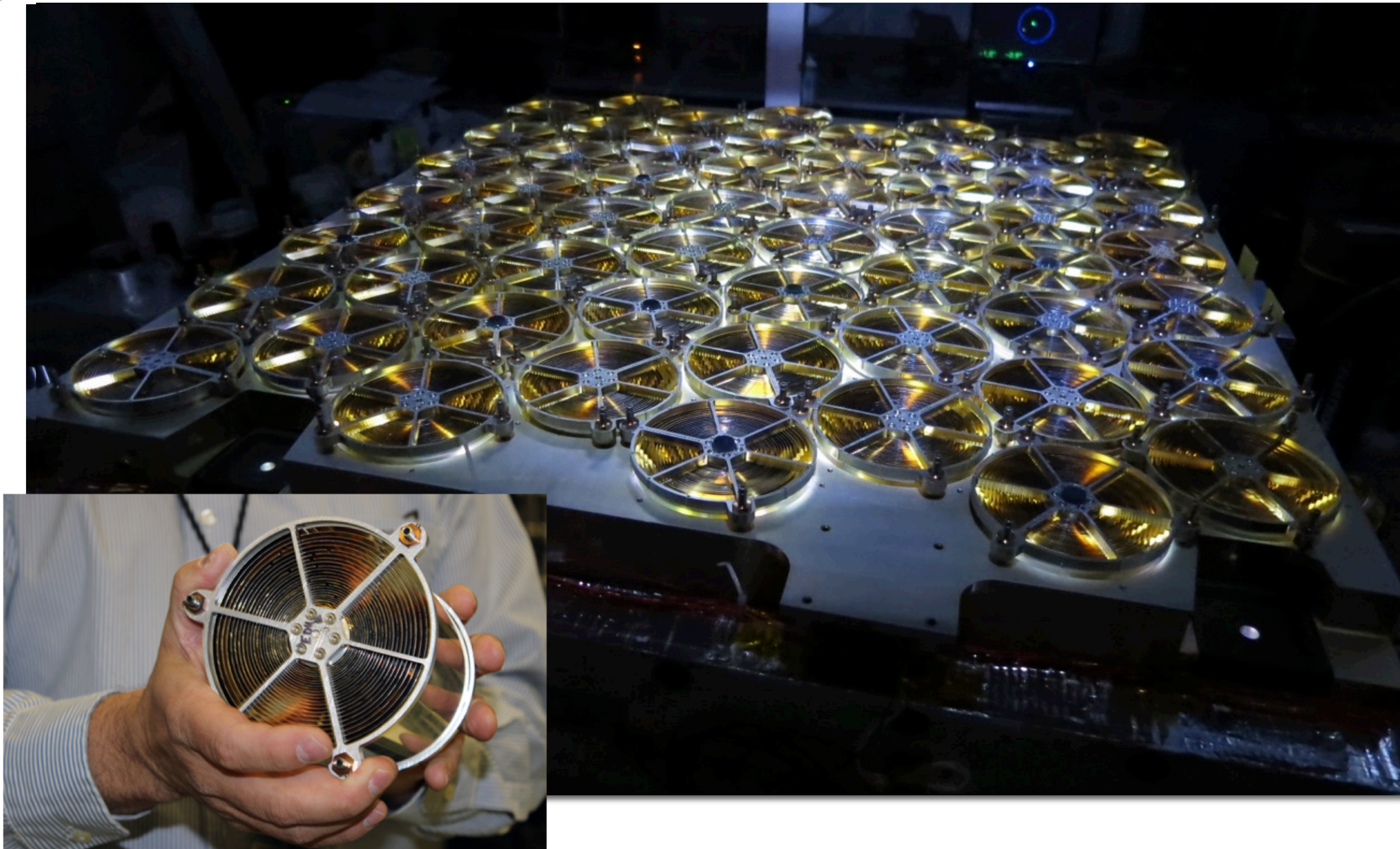
- Spectral band: 0.2–12 keV
- Timing resolution: < 100 nsec RMS absolute
- Energy resolution: 140 eV @ 6 keV
- Non-imaging FOV: 6 arcmin diameter
- Background: < 0.5 cps
- Sensitivity, $5\sigma$: $1 \times 10^{-13}$ erg/s/cm$^2$
  - 0.5–10 keV, 10 ksec (Crab-like)
  - ~3x better than XMM-*Newton*'s timing capability (PN clocked)
- Max countrate: ~38,000 cps (3.5 Crab)
  - Deadtime accounted for in telemetry



# The NICER Payload

# X-ray Concentrator optics

*Single reflection, grazing-incidence nested gold-coated Al foils*

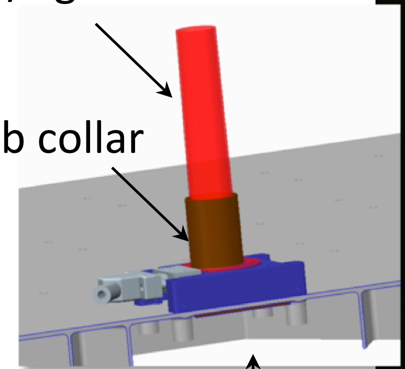


# Detector plate

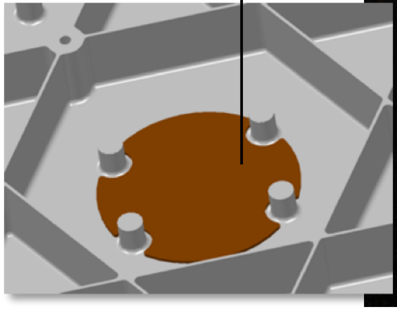
*Radiation shielding*

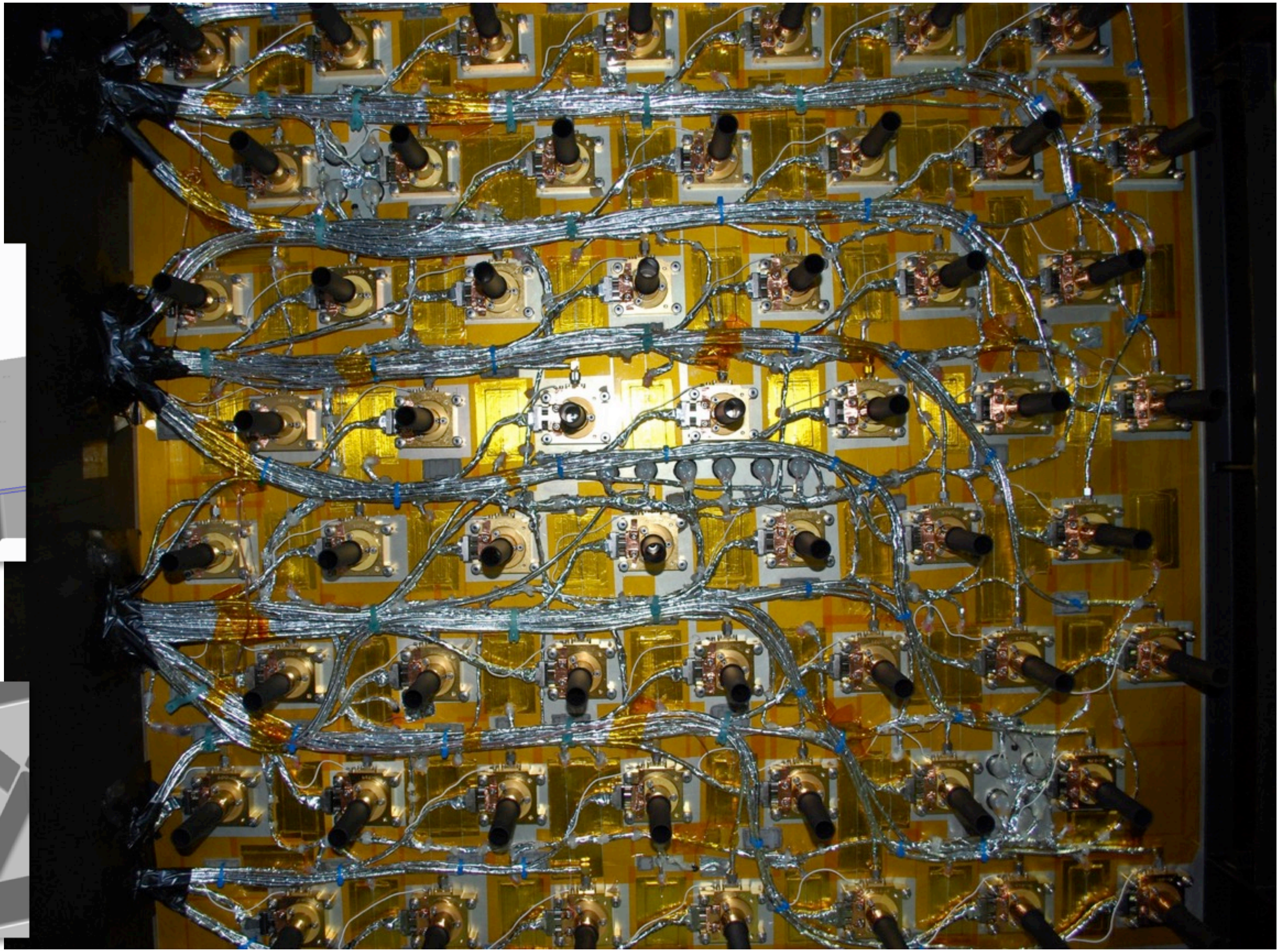
Au/Ag "traffic cone"

Pb collar



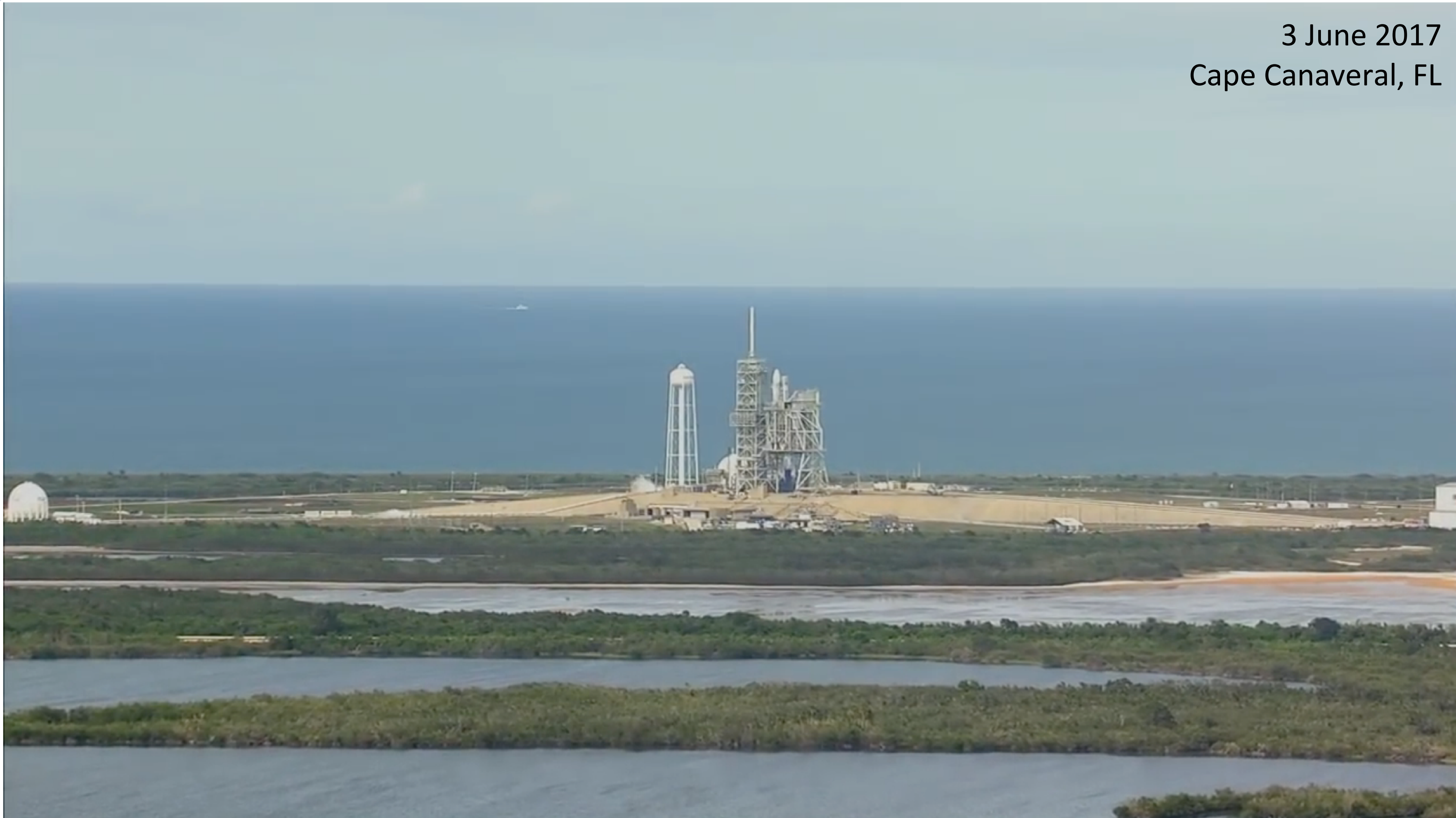
Pb disk





# NICER's ready to go!

# Launch!



# Transport and installation (cont.)

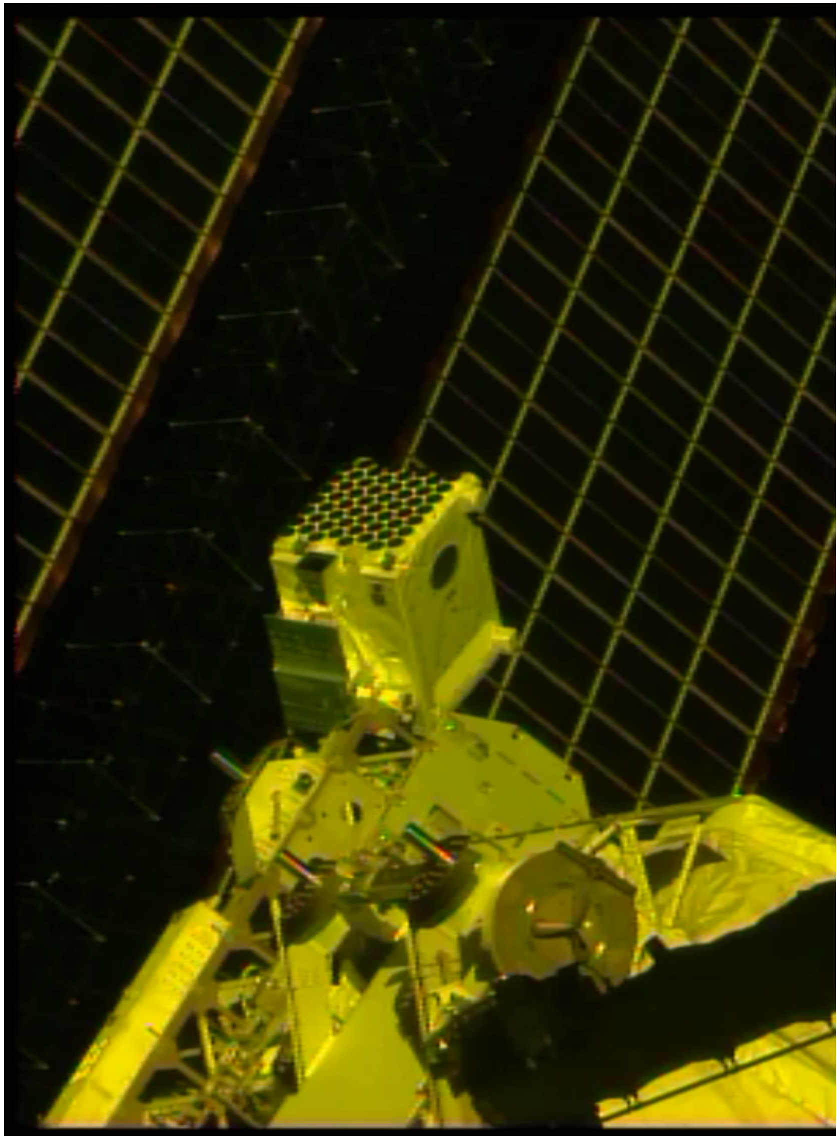
*Dragon and NICER proceed to ISS transfer orbit*

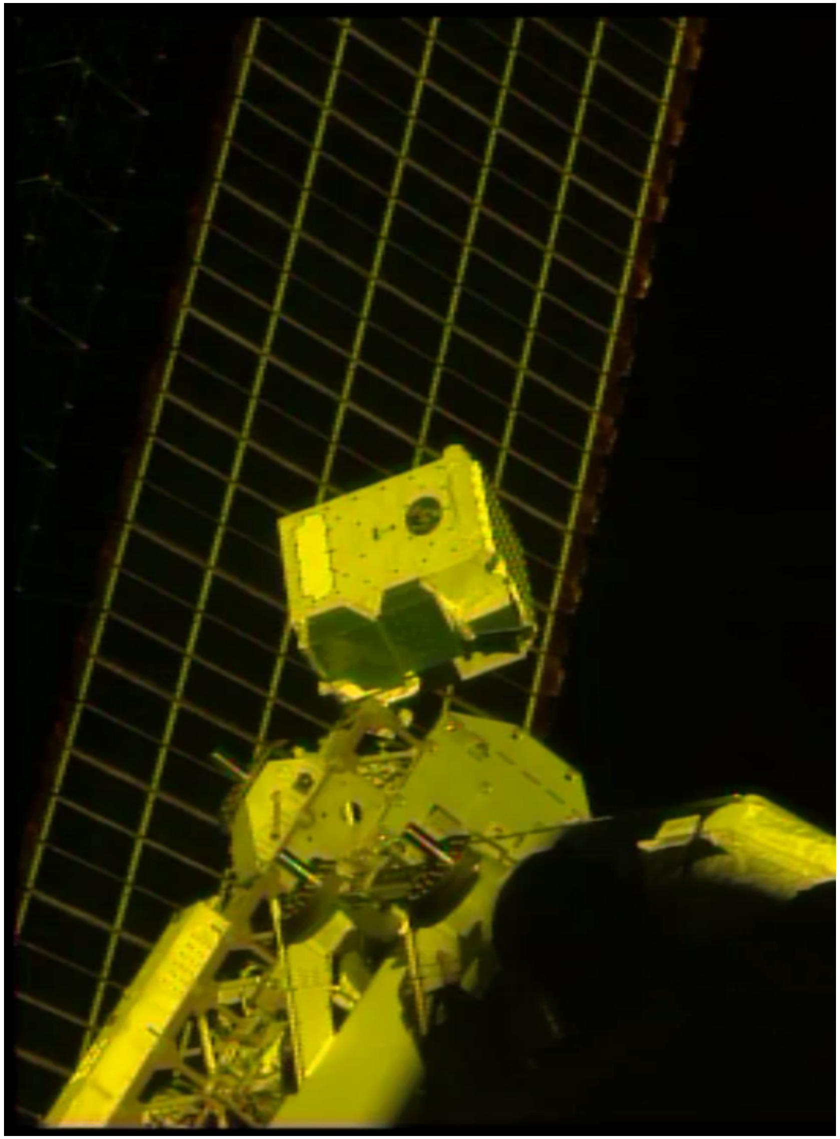
# Transport and installation (cont.)

*Extraction from Dragon was delicate…*

# Watch NICER collect your photons!

*Occasional / on-demand live ISS video*





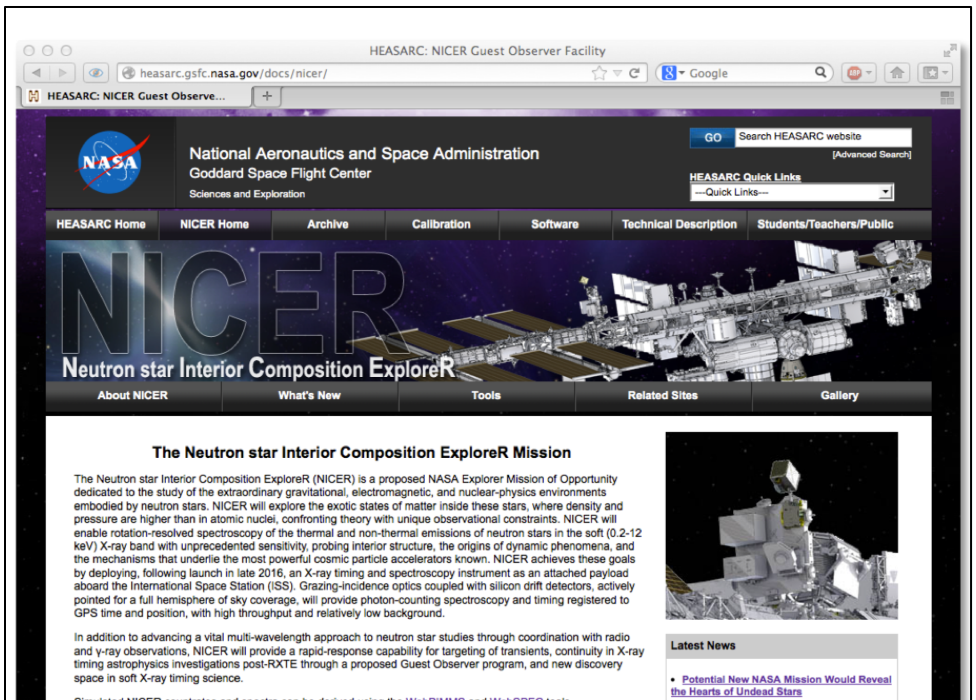
# Baseline Science and GO timeline

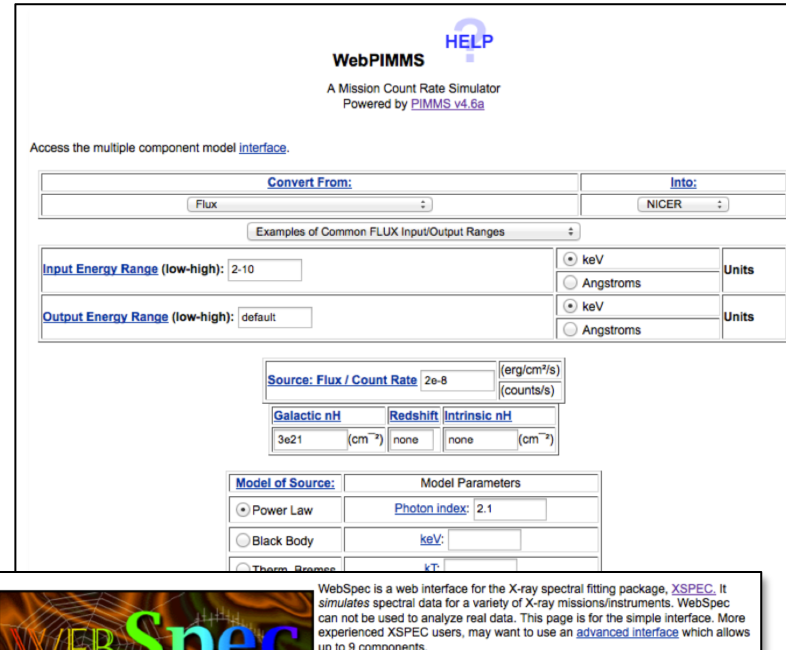
- **3 Jun 2017** — Launch
- **14 Jun 2017** — Activation
- **17 Jul 2017** — Beginning of Baseline Science ops
- **Fall 2017** — Establishment of NICER GOF; PI discretionary time requests considered
- **Feb 2018** — Release of NICER GO Cycle 1 call for proposals (ROSES), *observations contingent on mission "bridge" extension;* currently, no funding or data rights for GOs
- **March 2018** — First public data release to HEASARC
- **Jun 2018** — Mission Success Progress Review
- **Sept 2018** — Cycle 1 proposals due
- **Jan 2019** — End of Baseline Science mission; beginning of Cycle 1 GO observations *if mission bridge is approved.*
- **Spring 2019** — Consideration of NICER mission extension by Astrophysics Senior Review
- **Summer 2019** — Senior Review results announced
- **Oct 2019** — Bridge & GO Cycle 1 complete, possible 3-yr extension

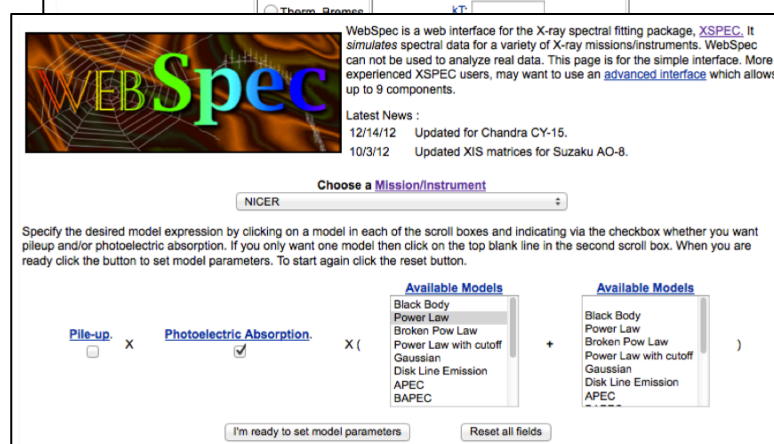
# Guest Observer Program

*NICER tools at HEASARC available to anticipate observations of your favorite targets*

- Timing-spectral studies of black-hole binaries & AGN
- Broadened iron lines
- Coronal emission from stars, other soft transients
- … and more!

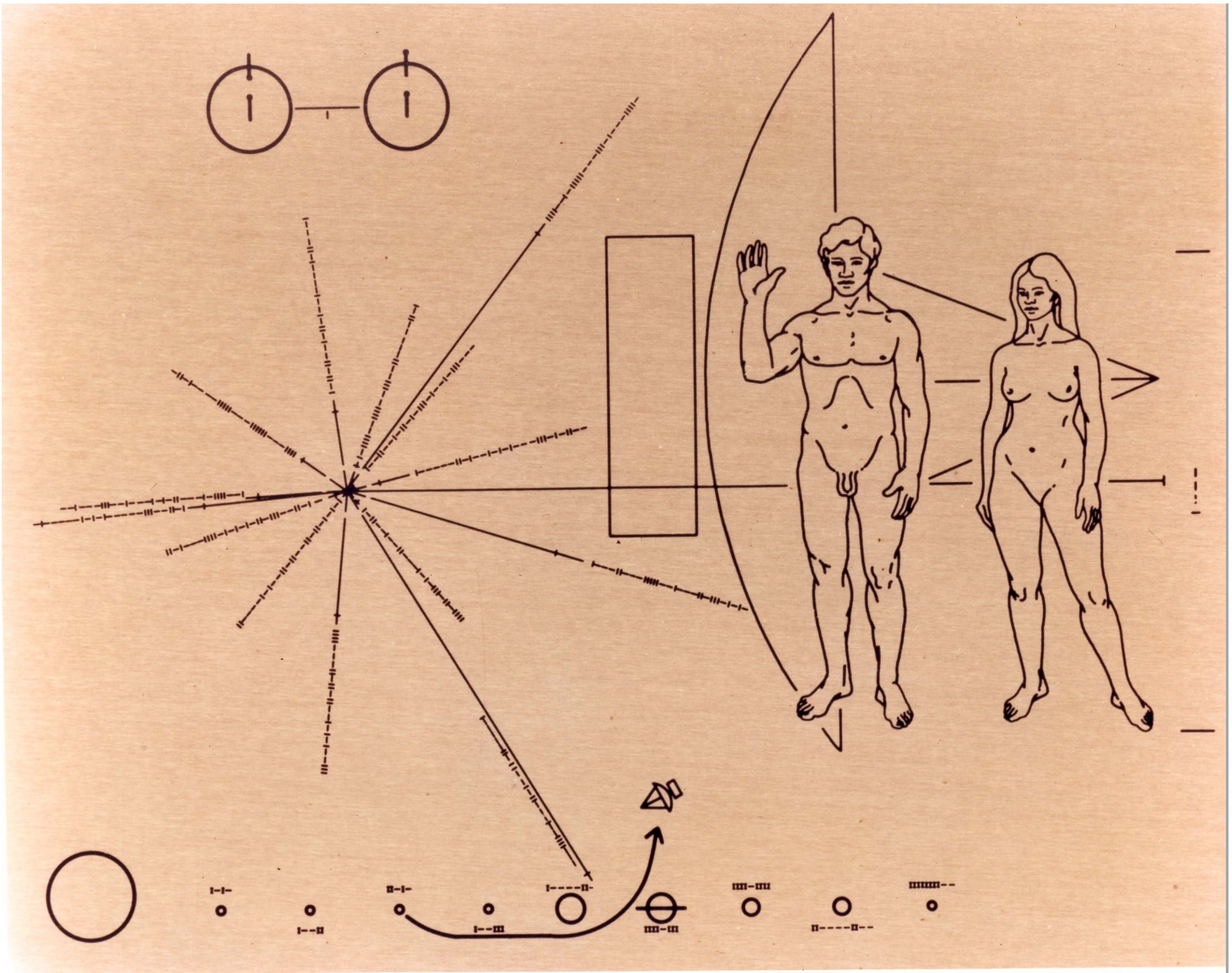


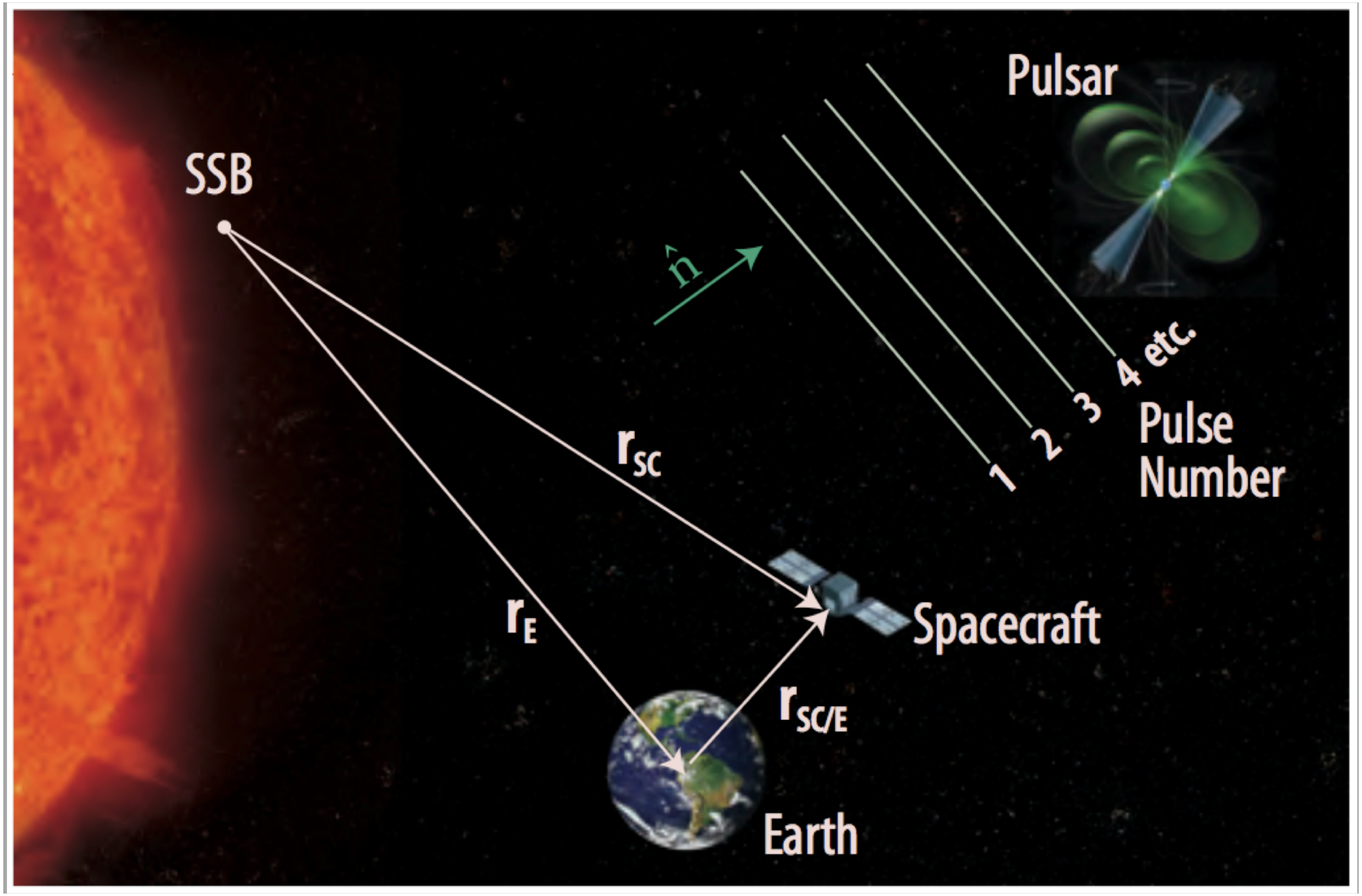
# SEXTANT — Heritage

## *Pioneer Plaques and Voyager Records*



# SEXTANT — Method

*Inverting traditional pulsar-timing techniques*

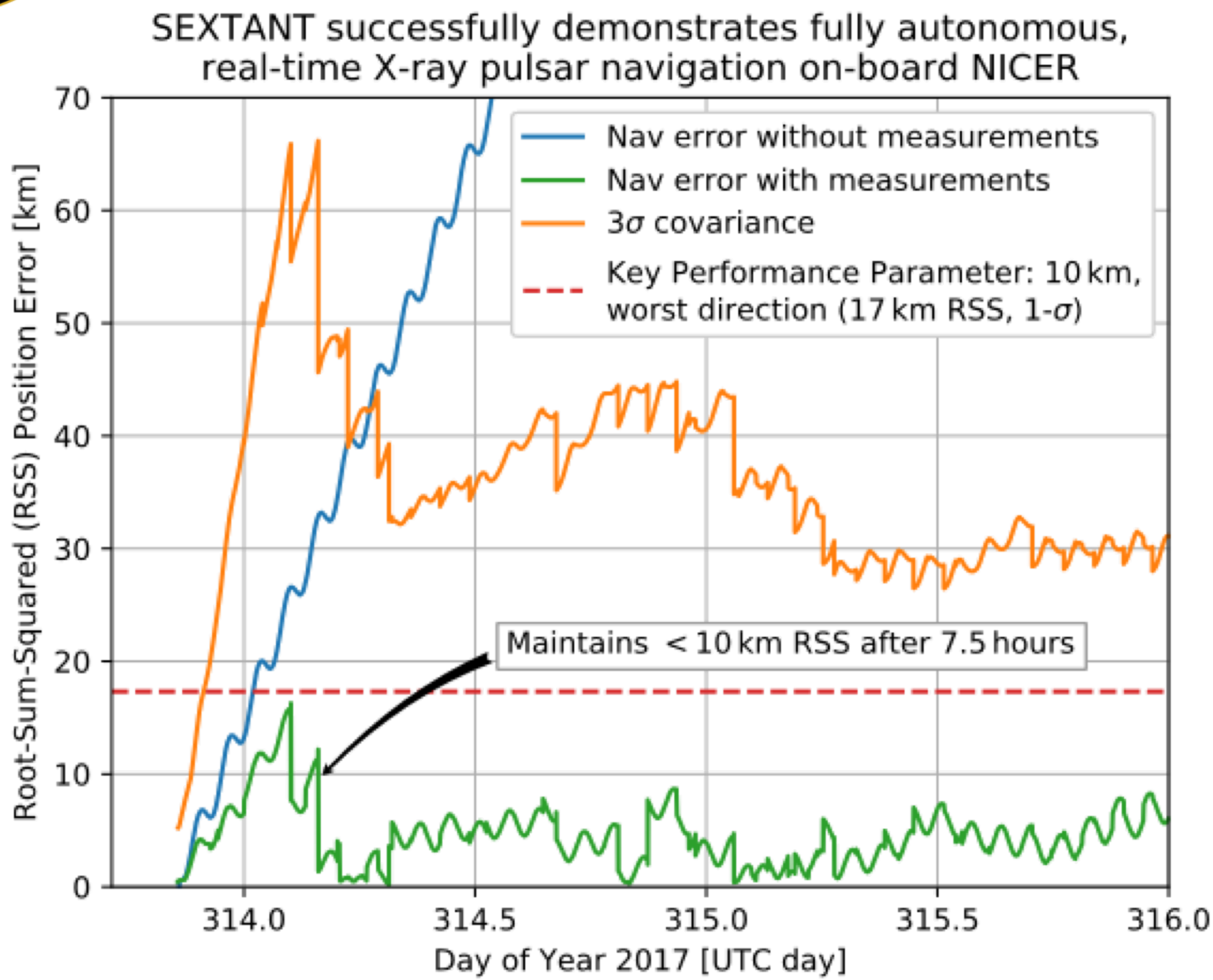


# SEXTANT — Deep-space navigation

## Objectives:

- Demonstrate GPS-like navigation anywhere in the Solar System using X-ray observations of millisecond pulsars (MSPs)
- Provide *first real-time, on-orbit demo* of X-ray pulsar-based navigation (XNAV)
  - Key Performance Parameter: better than 10 km worst-direction orbit determination in less than 1 week
  - Stretch Goal: better than 1 km in less than 2 weeks
- Determine practical limitations of XNAV
- Catalog and characterize addition “beacon” MSPs
- Assess the feasibility of pulsar-based time transfer and timescale

# Success!



SEXTANT successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER
Nav error without measurements
Nav error with measurements
3σ covariance
Key Performance Parameter: 10 km, worst direction (17 km RSS, 1-σ)
Maintains < 10 km RSS after 7.5 hours
Root-Sum-Squared (RSS) Position Error [km]
Day of Year 2017 [UTC day]
0
10
20
30
40
50
60
70
314.0
314.5
315.0
315.5
316.0

# *Observing the sky from ISS*